FARMING IN THE CITY: HOW THE URBAN ENVIRONMENT AFFECTS VEGETABLE CROP PRODUCTION, SOIL HEAVY METAL CONTAMINATION AND NUTRIENT DYNAMICS, PRODUCE NUTRITIVE QUALITY, AND INSECT DYNAMICS IN URBAN GARDENS

BY

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DISSERTATION

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Abstract

Urbanization is a growing trend worldwide and especially in industrialized countries, where urban populations have reached over 80% of total populations. Growing food in urban areas is common in developing countries and accounts for a significant portion of urban dweller's diet. Developed nations have long since relied on external production for urban consumption. Recently there has been increased interest in urban agriculture as a means of improving diet and reducing poverty in urban areas and to reduce externalities of a global food system. While there is significant understanding of the urban microclimate and ecosystem, there is little understanding of agricultural production systems in the urban environment. To assess the effects of urbanization on urban food production, six experimental gardens were established in 2013 from near to city center of Chicago to rural agriculture land along an urban to rural gradient near 45° 50' N. Each garden had 40 0.43 m^3 raised bed pots filled with compost-soil-sand mix (50, 40, and 10% respectively). Fourteen cultivars of seven common garden vegetable species were grown in the raised bed pots in 2013 to 2015 seasons. Onion and kale were planted in early April (spring), tomato, pepper, and snap bean was planted in late May (summer), and following the spring crops, table beet and Brussels sprout were planted in late July (fall). Two cultivars of each crop was planted in each pot and there were eight replications of each crop in each garden. Crops were sampled during the season for fruit quality, yield, and biomass. Structural equation models were used to compare crop yield to micrometeorological measures. Soil samples taken in the spring and fall as well as plant root simulator probes were used to assess soil nutrients, heavy metal contamination, and soil microbe dynamics. Fruit quality measures included soluble solids, total phenolic content (TPC), and two antioxidant capacity assays (FRAP and DPPH). Insect abundance and diversity was measures using yellow sticky traps and pheromone bait traps. Insect

pest infestations were quantified weekly through the growing seasons. Micrometeorological sensors adjacent to the gardens measured and logged temperature, humidity, wind speed, light irradiation, CO_2 concentration, and ozone concentration. Ozone levels were higher at peri-urban sites. Temperature, CO_2, and vapor pressure deficit were higher in urban sites and lowest in the rural site. Yield of spring and fall crops were generally higher in the urban sites and summer planted tomato and bean was higher in peri-urban and rural sites, whereas pepper had generally higher yield in urban sites. Measures of ozone (-), temperature (+), and growing degree days (+) had a causal relationships with spring and fall planted crops and not summer planted crops. Light interception (+), ozone (-), and distance to city center (mixed) had causal relationship to summer planted crops. Soil lead levels increased slightly over the three years, but no garden had higher lead levels compared among gardens. The compost based soil experienced leaching of calcium, potassium, and magnesium from the soil profile. Despite no fertilization, soil nitrate levels did not decrease, but actually increased due to soil maturation. A peri-urban garden with acidic irrigation water lead to high sulfate levels and reduced phosphorus and lead levels. Produce quality measure soluble solid was negatively related to yield and temperature and unrelated to FRAP, DPPH, and TPC assays. In some crops, soluble solids were greater in rural gardens. DPPH, FRAP, and TPC were positively correlated and were negatively associated with temperature, solar radiation, and vapor pressure deficit. TPC, FRAP, and DPPH were generally not different between garden locations. The common garden pest *Helicopvera zea* (corn earworm) had greater captures of the adult insect in rural gardens while aphid infestations were greater in urban gardens. Micrometeorological conditions affected plant growth, soil nutrients and microbial, and fruit quality dynamics along a rural to urban transect of Chicago, IL, but the difference does not affect the nutrient quality or safety of urban grown produce.

To my wife, Sara, and my
beautiful children
Moroni, Joseph, Mary,
Peter, and Penny

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CHAPTER 1: HOW DOES ENVIRONMENTAL VARIATION AFFECT VEGETABLE PRODUCTION ALONG AN URBAN TO RURAL GRADIENT?

Abstract

Urban food production has gained popularity and many cities are now recognizing food production as a viable urban land use. Little is known, though, on the effects of the altered growing environment on vegetable food production. A field experiment was started in 2013 to assess the effects of increased pollution and urban microclimatic conditions on vegetable crops. Six experimental gardens with forty 0.89 m^2 raised beds with a uniform compost, soil, and sand (50%, 40%, and 10%) mixture were established across a latitudinal transect of greater Chicago, Illinois constituting an urban to rural gradient. Seven vegetable crops (kale, Brussels sprout, pepper, tomato, beet, onion, and garden bean) were planted in early, mid, and late season plantings. Micrometeorological towers measured temperature, light irradiance, wind, CO_2, and ozone and were placed adjacent to each experimental garden. Yield of early and late planted Cole crops in 2013 and 2014 were greatest at urban sites. Onion yield was greatest at urban sites in 2014 and 2015, but yields were greatest at the most rural site in 2013. Yield of mid-season planted beans, tomatoes, and peppers were variable across the urban to rural transect without consistent trends. Beet yield was generally greatest at two peri-urban sites. Temperature was 1-2° C higher in the daytime and 2-4° C higher in the nighttime at urban sites compared to rural locations, but wind speed was greatest at rural sites. Ozone was 2× and 0.5× greater at peri-urban compared to urban and rural sites, respectively. Carbon dioxide concentrations were variable depending on season and traffic proximity. Structural equation models (SEM) were used to compare plant productivity to micrometeorological measures. Measures of temperature (+), ozone exposure (-), light interception (+), and vapor pressure deficit (+) were most highly correlated to productivity. Measures of ozone exposure is the factor that predicted plant productivity most significantly across the years and crops in the study. The urban heat island increased crop productivity, especially in early and late season crops. Increased tree canopy prevalence at peri-urban sites had a significantly negative effect

on productivity. SEM models generally explained between 30 and 50% of overall variation. Vegetable crop productivity appears to be aided by the increased temperature and reduced ozone of an urban environment, but crops in suburban areas adjacent to cities may be hindered by elevated ozone levels and urban tree canopies.

Introduction

Urban agriculture can be defined as all forms of food production that benefit from the infrastructure provided by human concentrations in towns or cities (Ellis and Sumberg, 1998; Vagneron, 2007). Urban agriculture is prevalent in emerging economies (Thebo et al., 2014) with up to 50% of urban land area under cultivation (Armar-Klemesu and Maxwell, 2000). Throughout the U.S., urban agriculture is a growing sector of local food economies although cultivated urban land for food is currently under 1% of total land area (Mok et al., 2011, DeLind, 2011). As the concentration of people living within urban areas around the world increases (Baker et al., 2002), urban agriculture is expected to contribute to food security, urban waste utilization, economic revitalization, and ecological benefits (Smit and Nasr, 1992; McClintock, 2010; Gupta and Gangopadhyay, 2013). Although the potential benefits are promising, there is limited science-based information available to urban farmers regarding the cultivation of plants in urban environments (Wortman & Lovell, 2013).

Urban ecosystems differ from natural ecosystems in many ways. The input of energy and resource transported into cities, defined as "urban metabolism" (Barles, 2010), create a net positive flux of carbon, pollutants, and heat in urban environments (Molina and Molina, 2004). Potentially harmful pollutant fluxes include primary (NO_x, SO_2, and PM_{10}) (Bereitschaft and Debbage, 2013) and secondary (peroxyacetyl nitrate, O_3, and ethylene) pollutants (Trusilova and Churkina, 2008). Carbon dioxide concentrations are higher in urban compared to adjacent rural areas (Bellucci et al., 2012). The increased surface albedo, material thermal admittance, and

reduced vegetative evapotranspiration lead to urban heat island effects (UHI). Additional stressors of urban plant growth include canopy light attenuation, altered pollinator to flower timing, inherent and deposited heavy metal contamination, and storm water runoff (Wortman and Lovell, 2013).

Urban ecosystems tend to be polluted, compared to rural ecosystems. Urban nitrous oxide concentrations (NO_x) and sulfur dioxide (SO_2) can reach two to five times levels observed in rural areas (Hewitt, 1991). High NO_x and SO_2 can reduce plant biomass and leaf area (Rowland A et al., 1984; Weigel et al., 1990), though urban concentrations in modern cities are usually not high enough for effect. Ozone fluxes and precursors to ozone production (volatile organic compounds (VOC) and NO_x) can be two to three times greater in urban ecosystems and are the most important aerial pollutants that affect crops (Krupa et al., 2001). Studies in field crops (Heagle, 1989) and tree canopies (Pye, 1988) have demonstrated reduced productivity of plants in response to long-term, moderate ozone exposure, even at basal levels. Ozone damage can be more severe in peri-urban areas than in city centers (Gregg et al., 2003) because the dynamics that favor ozone generation, such as high VOC and moderate concentrations of NO_X, are more common in peri-urban areas (Paoletti, 2009).

Concentrations of CO_2 are higher near city centers (George et al., 2007). Grimmond et al. (2002) found that CO_2 diurnal flux was higher in forested areas and rural gardens, but averages were higher in downtown Chicago, IL. Higher CO_2 levels can decrease stomatal conductance and lead to high water use efficiency and plant productivity, but can lead to additional heat stress because of reduced evaporative cooling (Leakey et al., 2009). Elevated ambient CO_2 can also accelerate infestations of some weed species and alter outcomes of interplant competition (Ziska et al., 2007).

Microclimatic conditions (temperature, light, and wind) vary in the city and are known to affect plant growth. The urban heat island (UHI) is well known (Arnfield, 2003) and clear models have been developed to relate urban structure, climate, and population to the UHI effect (Phelan et al., 2015). Thermally regulated ecological processes, such as germination, flowering, senescence, hatching, and morphogenesis may be affected by UHI in urban ecosystems. Urban grown plants may benefit from additional growing degree days and frost free days (Zhang et al., 2004a), but can also be subject to greater heat stress, vapor pressure deficit, and moisture stress (Cregg and Dix, 2001). In urban settings, the built surroundings and tree canopy can reduce crop light interception (Johnson et al., 2015) and increase cloudiness from larger surface boundary layers and particulate aerosol cloud seeding (Angevine et al., 2003). Wind speeds in cities are lower due to increased surface roughness and boundary layer (Coceal and Belcher, 2005), which can increase plant productivity in arid climates (Bang et al., 2010), but can also slow mixing ratios, concentrating pollutants (Chou et al., 2007).

Urban farms, community gardens, and home gardens produce mostly annual vegetable crops (Armar-Klemesu and Maxwell, 2000; Novo and Murphy, 2000). Because of the diversity of vegetable crops grown in urban areas (Taylor et al., 2016) and the number of potential environmental stressors, it is difficult to predict crop growth and yield response in the urban environment. High temperatures can be detrimental to growth or fruit set in Brassicaceae crops (Wurr and Fellows, 1991), Solanaceae crops (Erickson and Markhart, 2001), and Fabaceae crops (Konsens et al., 1991). Increased urban temperatures can also stimulate increased growth, especially in cool-season crops planted in spring or growing in the fall (Peet and Wolfe, 2000). Tomato (*Solanum lycopersicum L.*), onion (*Allium cepa L.*), lettuce (*Lactuca sativa L.*), radish, and pepper (*Capsicum annuum L.*), and bean (*Phaseolus vulgaris L.*). are crops highly sensitive

to ozone damage and yield loss, whereas broccoli (*Brassica oleracea L.*), kale (*Brassica oleracea L.*), cucumber (*Cucumis sativus L.*), and potato (*Solanum tuberosum L.*) are considered less sensitive (Mills et al., 2007; Wang et al., 2007). Ozone exposure can have negative effects on fruit set and yield of tomatoes (Gillespie et al., 2015) and other crops (Drogoudi and Ashmore, 2000). Because most vegetable crops use the C3 photosynthetic pathway they should experience significant CO_2 fertilization with higher CO_2, but actual levels observed in urban areas may not elicit a significant growth response.

An urban to rural ecological cline exists where a mixture of anthropogenic and natural factors are at play. The effects of urbanization mentioned above will apply with variation along this cline in various cities. The objective of this study was to quantify the microclimate and atmospheric CO_2 and ozone concentrations along an urban to rural gradient in greater Chicago, IL, and use this data to help explain measured yield variability of seven common vegetable crop species along the gradient.

Materials and Methods

Site Setup

To accomplish project objectives, six experimental gardens (sites) in the Chicago, IL area were established in spring 2013. Gardens were located along a latitudinal corridor close to 41° 50' N from the city center to rural agricultural areas (Fig. 1.1). Gardens were 75 m^2 and contained 40 raised-bed pots (0.43 m^3) (Smartpot™, High Caliper Growing Systems, Oklahoma City,OK) filled with a uniform 1:1 compost and soil mix (60% sand, 20% silt, and 20% clay) from a single source. Soil tests were done with sampled soil before raised bed establishment in March 2013 and from random six inch cores from 16 pots in April 2015 from each garden. Plant root simulator probes (PRS™, Western Ag Innovation, Saskatoon, SK) were buried in 16 pots in

each garden to test soil available metals and nutrients for two week periods in July 2014, May 2015, and September 2015. Tests indicated that soil nutrients were not limiting to plant production (Table 1.1). Soil moisture was measured continuously in five pots at 10 cm depth (Watermark sensors, IRROMETER Inc, Riverside, CA) and drip-irrigation emitters maintained soil moisture near field capacity. A randomized complete block split-plot design was used at each garden with crop species as the main-plot factor (i.e., one raised-bed pot) and cultivar as the split-plot factor (i.e., each half of a raised-bed pot). Each garden was divided into four blocks with eight replicates of each split-plot factor (two replicates per block).

Crop Production

Main-plot crop species treatments included table beet (*Beta vulgaris subsp. vulgaris*), kale, Brussels sprouts (*Brassica oleracea L.* spp. *gemmifera*), tomato, pepper, onion, and snap bean. Two cultivars (or subspecies) of each crop (typically one heirloom and one hybrid cultivar) were included as split-plot treatments to assess potential genotype by environment interactions (Table 1.2). Kale and onion were planted in early spring, harvested mid-summer, and those pots were subsequently replanted to beet and Brussels sprouts. This double-cropping strategy is common in intensive vegetable production and also allowed us to maximize the number of experimental treatments per season. All crops (except onions) were started from seed in a greenhouse and transplanted 3-8 weeks later (depending on crop) on the same day across all test gardens. Onions were purchased (Dixondale Farms, Carrizo Springs, TX) as onion starts and directly planted into the pots. Snap bean cultivars, R123 and S156, are lines from a cross of an ozone resistant cultivar "Wade" and susceptible cultivar "Oregon 91" and demonstrated unusual resistance (R123) and susceptibility (S156) to elevated ozone concentrations (Burkey et al., 2005). Sub-plot treatments included eight onion plants, five snap bean and beet plants, three Brussels sprout, kale, and pepper plants, and one tomato plant.

Pots were filled in March of 2013 and topped with 20 cm of the soil/compost mixture in March 2014 due to soil settling. All crops were treated according to organic principles in this study. Peppers were trellised with bamboo stakes with plastic rings attached around the main stem in mid-June. Tomatoes were trellised with cages starting mid-June and the heirloom cultivar, 'Virginia sweet', was pruned by cutting suckers (auxiliary buds) and leaving two main growing points. The cultivar 'Bush Goliath' was not pruned. Kale was harvested every two weeks starting mid-May by cutting the lower leaves at the main stem, leaving three fully emerged leaves after cutting. Summer crops tomato, pepper, and snap bean were harvested weekly as needed. Aphids on tomatoes were sprayed with an insecticidal soap or neem oil (Triple action neem oil, Southern Ag, Hendersonville, NC) as needed during the season. Brussels sprout seedlings were sprayed weekly with *Bacillus thuringiensis* subspecies *kurstaki* (Thuricide BT Caterpillar Control, Southern Ag, Hendersonville, NC) for the first 6 weeks in field to control cabbage looper (*Trichoplusia ni* Hübner) and imported cabbage worm (*Pieris rapae* L.).

Plant physiological response across gardens was quantified throughout the season with: 1) weekly measures of plant height, which was taken from height of newest fully emerged leaf and integrated across time points for relative growth rate; 2) bi-weekly leaf greenness readings with an atLEAF+ chlorophyll meter (FT Green LLC, Wilmington, DE) during early vegetative growth on newest fully emerged leaves; 3) weekly fruit yield as fruit matured; and 4) plant biomass at the conclusion of marketable harvests. All crops were indeterminate and harvested regularly, with the exception of beet, onion, and Brussels sprout, which were harvested one time on the same day across all gardens. Herbivory and pathogen infections were rated using a simple 0-100% scale of percentage leaf coverage by pests or percent of plant infected/damaged. Aphid ratings were done by estimating leaf coverage of crowds and prior leaf damage. Weekly ratings

of 0-100% coverage of bean leaves with ozone like damage (interveinal browning and chlorosis) were taken after injury was manifest rated on each plant then averaged across the five plants in each sub-plot. Ratings were taken on each cultivar within each pot by the same individual each week.

Micrometeorological Measures

Weather towers were located directly adjacent to each experimental garden and equipped with micrometeorological and trace gas sensors, and data loggers (CR10X, Campbell Scientific, Logan, UT). Sensors included a HMP45 temperature and relative humidity probe (Campbell Scientific, Logan, UT), cup anemometer and wind vein (Davis Instruments Corp, Hayward, CA), SP-110 pyranometer (Apogee Instruments Inc., Logan, UT), SBA-5 CO_2 infrared gas analyzer (IRGA) (PP Systems Inc., Amesbury, MA), and an F-12 toxic gas analyzer with 0-1000 parts per billion (ppb) ozone sensor (Analytical Technology, Inc., Collegeville, PA). Three gardens (Kuipers, Cantigny, and Garfield; Fig. 1.1) had ozone sensors in 2013 and 2014 and all gardens had ozone sensors in 2015. A CO_2 IRGA was not included at the Growing Home garden in any year. Missing data from logger or equipment malfunction was filled by comparing neighboring gardens, alternate years, and data before and after missing data. If missing data was over two days length, a regression model was made with the adjacent gardens data and applied across the whole year to assess fit before filling. Imputation methods were used when possible on measures with low inter-period variability such as wind speed and CO_2 concentration, but imputation method filling was not used or appropriate for measures with high periodic variability such as temperature and ozone. Overall, missing data accounted for less than 2% of collected data.

Data from each sensor was collected continuously and a one hour average, maximum, and minimum values and cumulative measures were calculated. Integrated statistical measures

were formulated from the measured variables. Growing degree day (GDD) was calculated from the formula:

$$GDD = \sum_{t1}^{tn} If\ T_{ah}(t) \geq T_b\ ;\ then\ (T_{ah}(t) - T_b)/24$$

where T_{ah} is the average hourly temperature, T_b is the base temperature of the crop (4°C for kale, onion, beet, and Brussels Sprout and 10°C for tomato, pepper, and beans), and *t* is the hourly time period. This was integrated across the cropping period from crop transplanting to final harvest. Ozone accumulated measure AOT40 (Accumulated Ozone exposure above the Threshold of 40 ppb h^{-1} for vegetation) was calculated using the formula

$$AOT40 = \sum_{t1}^{tn} If\ Z_h(t) \geq 40;\ then\ (Z_h(t) - 40)$$

where Z_h is the hourly ozone average in ppb and *t* is the hourly time period. These were summed over the growing period for each crop. The other ozone statistic is SUM06 which is the sum of hours where average ozone concentration is over 60 ppb. Radiant exposure is the total light energy received on a surface and was calculated by the equation:

$$H_e = 3600 \cdot Ee$$

where *Ee* is the surface irradiance measured from the pyranometer in $W \cdot m^{-2}$ and H_e is the radiant exposure in $J \cdot m^{-2}$. This was calculated for each hour and integrated across the season for total radiant exposure. Sun hours were calculated by summing the number of hours where the light radiation was greater than 65% of the maximum radiation during that hour; maximum hourly radiation values were retrieved from SolarCalc 1.0 software (http://www.ars.usda.gov/). A fish eye lens camera and ceptometer bar were used to calculate average canopy light transmittance coefficient (TrCoef) and leaf area index (LAI) at each garden by integrating canopy tree and building cover over the canopy picture (CI-110 Plant Canopy Imager, CID Bioscience Inc.,

Camas, WA). No distinction was made between buildings and foliar canopy for LAI or TrCoef. Vapor pressure deficit (*VPD*) was calculated from relative humidity (*RH*) and average temperature (T_a) using the equation:

$$VPD = vp_{sat} * (1 - RH) \text{ where:}$$

$$vp_{sat} = e^{-1.88x10^4/T_a - 13.1 - 1.5x10^{-2} * T_a + 8x10^{-7} * {T_a}^2 - 1.69x10^{-11} * {T_a}^3 + 6.456 \ln T_a}$$

and represents the deficit of moisture relative to a saturated state. Distance to city center was a simple measure of distance of a garden from the same point inside the loop in downtown Chicago using the Google Earth (Google Inc., Mountain View, CA) measurement tool.

Statistical Analysis

Statistical analysis included a combination of generalized linear mixed models to assess the influence of site-years on crop response variables using the 'nlme' package (Pinheiro et al, 2015) in R version 3.2.1 (R Core Team, 2015). For the split -plot analysis, fixed effects included cultivar and block and random factors included year and site. Each crop was analyzed separately due to interactions with cultivar. Means comparisons were done using the Tukey HSD test from the 'multcomp' package (Hawthorn et al, 2008) in R.

Structural equation models (SEM) identify putative causal pathways from manifest (measured) and latent (combined measures and estimated factors) variables to understand the variation from response variables (Grace, 2006). Pathway models take known relationships between factors or variables and hypothetical relationships and then use observational data to confirm relationships and quantify causal strength of association between variables (Grace, 2006). Assumptions for SEM include the correct pathway construction based on prior knowledge or proper interpretation of relationships of the variables and the assumption that extraneous factors are accounted for (Kline, 2015). For the first assumption we sought to establish the causal

links previously reported in the scientific literature between environmental factor measured (e.g., weather and pollutants) and crop response. The second assumption cannot be fully met in a true observational study, but proper experimental design can help minimize external variation. For example, this study was designed to eliminate belowground variation among gardens (e.g., uniform soil source and management) to focus on the effects of aboveground factors on urban crops.

Structural equation models were used to explore complex relationships among microclimatic factors, pollutants, and plant physiological response of each crop using the 'lavaan' (Yves Rosseel, 2012) package in R version 3.2.1 with grouping factors of crop and cultivar. Because there was no site level replication of micrometeorological measures, there were eighteen site-year replications of the study (three years × six sites). Growing season averages, maximums, and minimums for measured environmental factors and integrated measures discussed previously were compared to average garden yields or biomass of each cultivar. Models were compared using goodness of fit (χ^2), AIC, BIC, root mean squared error association (RMSEA) and comparative fit index (CFI). Comparison statistics were used on χ^2 and AIC using Akaike weights to find best models (Table 1.3, Tables 1.5-1.11). Models were determined using these goodness of fit and comparison indices, generally models with less predictor variables were better fitting and the best fit models were usually clearly chosen among models. The grouping factor, 'cultivar,' was used to compare the two cultivars within a single crop model, but unique causation coefficients were generated for each cultivar. Response variable error (E1 and E2) are measures of unexplained variation in the model and is calculated from 1-R^2 for each cultivar. Correlations between manifest and latent variables are standardized between-factor correlations to reduce scale bias.

Results

Micrometeorological Measures

Micrometeorological measures from spring (onion and kale growing season), summer (tomato, pepper, and bean growing season), and fall (beet and Brussels sprout growing season) are presented in Fig. 1.2, 1.3, and 1.4, respectively, and are an aggregation of data across 2013, 2014, and 2015. For the purposes of discussion, test gardens were classified as urban (Garfield Park and Growing Home), peri-urban (Cantata and Cantigny), and rural (St. Charles and Kuipers) based on their proximity to the Chicago city center (Fig. 1.1). These categories are somewhat subjective and specific to our experimental locations, but the groups are helpful in making generalized observations about plant and microclimatic responses in this study.

Over the course of the experiment, temperature averages were 1.7°C (nighttime) and 0.7°C (daytime) greater at combined urban compared to combined rural gardens. The UHI effect was smallest in spring (0.9 °C and 0.4 °C warmer urban nighttime and daytime temperatures, respectively; Fig. 1.2), intermediate in summer(1.7 °C and 1.0 °C warmer urban nighttime and daytime temperatures, respectively; Fig. 1.3), and greatest in the fall (2.5 °C and 1.3 °C urban nighttime and daytime temperatures, respectively; Fig. 1.4). Relative humidity (RH) at rural gardens was 11% and 5% greater than urban and peri-urban gardens, respectively. Vapor pressure deficit (VPD) was inversely related to RH and was 33% greater at urban gardens compared to rural gardens. Carbon dioxide was over 20 ppm greater at urban gardens versus rural gardens. However, one rural garden (St. Charles) was located adjacent to a busy road and had daily spikes of CO_2 and greater averages in spring and summer than the other rural garden (Kuipers; Fig. 1.2 and 1.3). Nighttime average CO_2 was 6% greater than daytime, although the differences between night and day were only 3% at the urban garden Garfield. Summer average

CO_2 had greater variability as seen in the larger inner quartile range of boxplots (Fig. 1.2-1.4). Light irradiance was not different among gardens in the spring (Fig. 1.2) presumably because the tree leaf canopy had not fully developed, but in the summer and fall (Fig. 1.3 and 1.4) the peri-urban and urban gardens received 10% less light irradiance than the rural gardens.

Ozone monitors were installed at three gardens in 2013 and 2014 (one rural, one peri-urban, and one urban garden) and all six gardens in 2015 (Fig. 1.2, 1.3, and 1.4). Averaged across all three years, average ozone concentration was two times greater at a peri-urban garden, Cantigny, compared to Garfield and Kuipers. Ozone average concentrations were 10% greater at the urban garden, Garfield, compared to the rural garden, Kuipers. In 2015 a peri-urban garden, Cantata, had two times greater ozone concentrations than the other gardens. Peri-urban gardens averaged 90% higher ozone than rural gardens and 106% of urban gardens. Maximum ozone concentrations were different among years, with 2015 having the lowest values.

Cumulative GDD base 10°C were 12% greater in the city than at the rural gardens (Table 1.4). Similarly, growing degree days base 4°C were 9% greater in the city than at the rural gardens. Frost free days increased by an average of 19 days in the urban environment across three years (13, 9, and 35 in 2013, 2014, and 2015, respectively, between rural and urban gardens) (Table 1.4). Combined ozone measures, SUM06 and AOT40, were greatest at peri-urban gardens similar to the overall ozone averages. Radiant exposure and average light irradiance over the three seasons was greatest at rural gardens and lowest at peri-urban gardens (Table 1.4 and Fig. 1.2, 1.3 and 1.4). Similarly, the peri-urban gardens had reduced transmission coefficients (TC) of 0.57 and high LAI measures of 0.46, whereas rural and urban gardens had TC averaging 0.94 and 0.92 and a LAI of 0.13 and 0.14 respectively (Table 1.4).

Crop yield

Spring- and fall-planted kale and Brussels sprouts, which are both of the cool season *B. oleracea* species, had significantly greater production in urban gardens in 2013 and 2014, and greater production overall in the rural garden St. Charles in 2015 (Table 1.2). Fall-planted Brussels sprouts did not have measurable sprout yields outside of an urban garden, Garfield, in 2013 and 2014, but in 2015 sprout yields were higher across all gardens (data not shown). In 2013, spring planted onion had greatest yield in the most rural garden (Kuipers), but in the other years the urban gardens had significantly greater yield. Yields of spring-planted kale and onion in 2014 had highest yield in urban gardens. Fall-planted beets had an unusual response. In 2013, beets had greater, though not significant, production in peri-urban gardens, but in 2014 and 2015 had greatest yield in urban gardens and least yield in peri-urban gardens. With the exception of 2013 beets, spring and fall crops had significantly reduced yields at the peri-urban garden, Cantata (Table 1.2).

Summer-planted tomatoes typically had greatest yields in rural gardens, followed by peri-urban gardens, except in 2013 when yields for the cultivar "Bush Goliath" were greatest at an urban garden (Garfield; Table 1.2). Summer planted peppers had greatest yield in urban and rural gardens in 2013 and 2015, but greatest yield in the peri-urban garden, Cantigny, in 2014. Pepper yield was 70% greater overall in 2014 than the other two years. The snap bean line R123 had less variability in yield compared to S156 among gardens. Snap beans had slightly greater yields overall in rural gardens in 2013 and 2015 and urban gardens in 2014. Overall bean yield was 75% higher in 2014 than the other years. Bean yield were reduced in 2015 at the peri-urban garden, Cantata, by rabbit damage soon after planting.

Overall, crop yields were greatest at the Garfield urban garden in 2013 and 2014 and greatest at the St. Charles rural garden in 2015. The peri-urban garden Cantata had the lowest overall yield in every year when combining all the individual crop responses. Within years, crop cultivars generally followed the same trends among gardens, although when comparing cultivars within crop species, yield was 62% greater for hybrid kale ('Winterbor'), 45% higher for hybrid pepper ('Bounty') and two times greater in 2015 for heirloom tomato ('Virginia Sweet').

Structural equation models

The χ^2 goodness of fit test was not significantly different from the data covariate structure for any of the SEM models developed for individual crops, which suggests the modeled covariate structure fits the variability in the data (Table 1.3). Coefficient of determination (R^2) for SEMs of cultivars of each crop compared to crop response were between 0.300 and 0.952 and were all significant indicating that the crop response variation was explained by the models. All SEM models presented met or were close to the criteria of a CFI value greater than 0.95 and an RMSEA less than 0.05 (Table 1.3).

An important predictor of plant response across gardens and years was ozone, including average concentration, average concentration during the daytime, and AOT40. Yield of spring crops (kale and onion, both cultivars) and one of the fall crops (beet, both cultivars) were negatively influenced by elevated ozone concentrations (Fig 1.5, 1.6, and 1.11). Both cultivars of snap beans were negatively influenced by ozone, although the effect on yield of S156 was more pronounced. The greatest ozone concentrations were recorded at the peri-urban gardens, which corresponded to the lowest combined yields across all crops and years. Surprisingly, one tomato cultivar was positively influenced by elevated ozone ('Bush Goliath' tomato) (Fig. 1.9). The

tomato cultivar ‘Virginia Sweet’ and beet cultivar ‘Merlin’ demonstrated a positive response to increasing CO_2 concentration ($P < 0.01$) (Fig. 1.9 and 1.10).

Another important predictor of crop yield was light, which includes measures of average light irradiance, total radiant exposure, and canopy light transmission (LAI and TrCoef). Light positively influenced ($P < 0.01$) yield of all summer-planted crops except the heirloom tomato cultivar ‘Virginia Sweet’ (Fig. 1.7, 1.8, and 1.9). Additionally, measures of light positively influenced ($P = 0.004$) the heirloom cultivar of fall-planted beet, ‘Chioggia’ (Fig. 1.10). Only one cultivar, ‘Toscano’ kale, was negatively influenced by a light-related factor (Fig. 1.5).

Temperature measures and GDD were important factors in explaining yield variability of spring and fall-planted crops. Increasing GDD positively influenced spring-planted kale ($P < 0.001$) and onion ($P < 0.01$) yields (Fig. 1.5 and 1.6) and increasing average temperature positively influenced biomass of fall-planted Brussels sprout ($P < 0.001$) (Figure 11). Measures of temperature did not explain variability in summer crop yields among gardens. Yield of the heirloom tomato, ‘Virginia Sweet’, was positively influenced ($P < 0.001$) by distance to city center; whereas yield of the heirloom cultivar of pepper, ‘Antohi Romanian’, was negatively correlated with distance to city center ($P = 0.015$) (Fig. 1.8 and 1.9). Wind speed differences were large between gardens (Fig., 1.2, 1.3, and 1.4), but the negative effects of wind were only evident in the SEM for snap bean S156 ($P = 0.034$) (Fig. 1.7).

Within each crop, cultivars of kale, onion, pepper, and Brussels sprout were influenced similarly (i.e. the sign and magnitude of the coefficients) by latent and manifest variables from micrometeorological measures (Fig. 1.5, 1.6, 1.8, and 1.11). Tomato, snap bean, and beet cultivars had differing influences from environmental measures. The tomato heirloom cultivar ‘Virginia Sweet’ was positively influenced by increasing distance to city center (i.e. yield

increased further from the city) and CO_2 concentration while the hybrid cultivar 'Bush Goliath' was positively influenced by O_3 concentration and canopy light admittance (Fig. 1.9). The heirloom beet cultivar 'Chioggia' was positively influenced by the light radiance factor and negatively affected by ozone; the hybrid cultivar, 'Merlin' was also negatively affected by ozone, but was positively influenced by CO_2 (Fig. 1.10). The snap bean cultivar S156 was negatively affected by the wind factor, but the R123 cultivar was not (Fig. 1.7).

Correlations of the predictor variables can be used to anecdotally validate SEMs against the raw environmental and yield data. The SEM manifest and latent variables correlation coefficients, for the most part, follow logical trends of meteorological measurements. For example, in the tomato SEM model ozone was negatively correlated with light and indeed, gardens with elevated ozone also had low overall light intensity and total light irradiance (e.g., Cantata) and CO_2 was negatively correlated with distance to city center (CO_2 decreased with increasing distance from city center, Fig. 1.9).

Discussion

Micrometeorological Measures

Most micrometeorological measures were similar to the measures hypothesized in Wortman and Lovell (2013) (Fig. 1.12). The magnitude of the urban heat island (UHI) effect during daytime and nighttime hours was consistent with with Ziska et al. (2007) in Baltimore, MD and Ackerman (1985) in Chicago, IL. However, other studies have reported much larger UHI effects (Oke, 1973; Gallo et al., 1993). Relatively minor UHI effects in Chicago is likely due to an almost constant south-westerly wind (Illinois State Water Survey 2016) and its proximity to Lake Michigan. Similarly, a study of Madison, WI found that lake effects, wind, and cloud cover all reduced UHI effects over 2012 and 2013 (Schatz and Kucharik, 2014). The

observed increase of 19 frost free days at urban locations was similar to a MODIS study of urban plant phenology, where there was a 15 day average extension of the growing season among North American cities (Zhang et al., 2004b). Vapor pressure deficit (VPD) measures in this study and the hypothesized levels of Wortman and Lovell (2013) were very similar, especially during the summer months. Higher VPD in urban areas has been shown to cause moisture stress and reduced plant growth (Kjelgren and Clark, 1992; Cregg and Dix, 2001), although the constant maintenance of the soil in this experiment near field capacity eliminated potentially negative effects of elevated VPD.

Reduced light irradiance at urban gardens may be explained by a reduced number of sun hours (Table 1.4). Peri-urban gardens had fewer overall sun hours due to canopy attenuation of light and urban areas presumably had fewer sun hours than rural gardens due to increased cloudiness. Increased cloudiness in urban areas has been documented by Angevine et al. (2003) where they found that the mixing boundary layer was significantly taller in an urban area compared to an adjacent rural area leading to increased cloudiness and lower wind speeds.

Ozone measures from this study did not match the hypothesized ozone levels in Wortman and Lovell (2013), where ozone was expected to be greatest in downwind rural areas. The major differences in ozone levels of this study were found at the peri-urban garden, Cantata, where ozone was consistently 1.5 to 3 times the level of the other gardens. Ozone formation is dependent upon several factors including NO_X concentration, light irradiance intensity, temperature, and presence of organic catalysts (Calfapietra et al., 2015). Cantata was located within the edge of the Cook County Forest Preserve (a large forested strip surrounding Chicago proper) where volatile organic carbon (VOC) from tree canopies meets the NO_X from vehicle exhaust from the city and ozone formation is favorable (Kleinman et al., 2002). Although VOCs

were not measured in this study, tree canopies are major sources of many types of VOCs (Chameides et al., 1992). Ozone at the Growing Home garden was less than the other gardens and is consistent with hypothesized levels (Wortman and Lovell, 2013). However, elevated ground level ozone in the peri-urban zone (Cantata) appears unique to Chicago because most studies report elevated ozone in adjacent rural zones (Zheng et al., 2010; Calfapietra et al., 2015). This discrepancy in the literature may be related to the definitions of peri-urban and rural, which are subjective. Moreover, the spatial distribution and abundance of vegetative canopy will differ among cities. Klumpp et al. (2006) found higher suburban ozone levels than rural and urban gardens in ten cities in Europe, but only a few rural gardens were included in the study.

Carbon dioxide levels were lowest in the rural garden, but otherwise levels were similar between peri-urban and urban gardens. This result is in contrast to Ziska et al. (2007) who found CO_2 levels were 60-70ppm higher in the urban center than the peri-urban and rural garden and similarly higher than this study. Higher CO_2 concentrations in Baltimore City is possibly due to the bowl shaped topography reducing atmospheric mixing. A study similar to this paper is ongoing in Salt Lake City which has bowl shaped topography and the city center has similarly elevated CO_2 concentrations to Baltimore (Christy Clay, Westminster College, personal communication, May 16, 2016).

Wind speed measures were taken at 2 m height and were consistently higher in the rural gardens as hypothesized in Wortman and Lovell (2013), but peri-urban gardens had reduced wind speed compared to urban gardens (Fig. 1.2, 1.3, and 1.4) due to increased prevalence of wind-blocking trees as is evident by the greater transmission coefficients at peri-urban gardens (Table 1.4). The urban garden, Garfield, had higher wind speeds than the other urban and peri-urban gardens which may be due to wind channeling (Dutt, 1991) at the garden.

Structural Equation Models

Spring-planted onions and kale and fall-planted Brussels sprouts were positively influenced by latent variables of temperature and GDD. Additional thermal accumulation (GDD) in the spring and fall as well as increased frost free days at the urban gardens likely contributed to earlier growth and greater yield of cool season crops planted in the spring and fall. Ziska et al. (2007) found earlier establishment and biomass accumulation of *Ambrosia trifida* in the urban center compared to an adjacent rural area of Baltimore, MD. The UHI effect is driven in part by material with greater thermal admittance, which is typically more prevalent in city centers than peri-urban gardens (Huang et al., 2011). Thus, advantages of earlier spring and later fall thermal accumulation would be expected in higher density urban centers. Summer crops were not strongly influenced by temperature or thermal time, which suggests that rural summer temperatures, while less than urban, were not limiting crop growth and yield.

The original hypothesis was that elevated urban temperatures and pollutant loads would cause differences in vegetable crop physiology and yield across the urban to rural transect (Wagstaff and Wortman, 2013). While ozone and temperature were important factors, latent variables related to light seemed to explain the most variability in yield among all crops. This difference was most pronounced in summer crops where light irradiance, total radiant exposure, or canopy light measures (LAI and TrCoef) were the most dominant drivers of yield variability in five of the six tested cultivars. Johnson et al. (2015), using modeled data, found that light attenuation can reduce productivity of snap beans in urban gardens by about 3.5% in a densely populated suburban area; however, this yield loss estimate is modest compared to the observed 11% reduction of snap bean yields in this study from all seasons when comparing peri-urban to rural (Figure 7), although Johnson et al. were not accounting for possible pollution effects. Urban

farmers should be aware of the likelihood of light attenuation in the city and the potentially severe yield penalty, depending on crop species. The heirloom kale cultivar, 'Toscano,' was negatively influenced ($P = 0.038$) by the latent variable canopy transmittance (Figure 5). A possible explanation for this may be that at gardens with high yield potential and high light levels, the hybrid cultivar, 'Winterbor,' was more competitive and caused a reduced growth of 'Toscano' cultivar in the shared pots The competitive advantage of 'Winterbor' over 'Toscano' is evidenced by greater yield across all gardens and years (Table 1.2).

All spring and fall-planted crops were all negatively influenced by at least one measure of ozone. Leafy vegetable crops, beets, and onions have all demonstrated sensitivity to ozone (McCool et al., 1987). Summer-planted crops, tomato and snap bean, were also influenced by ozone, although the model for tomato suggests ozone positively influenced yield. There is no physiological basis for a positive yield response to ozone and there is no evidence of a similar response to ozone for any crops in the scientific literature. This anomaly in the tomato model may be explained by covariation of environmental factors because ozone and canopy light admittance were negatively correlated (Fig. 1.9). Yield of 'Bush Goliath' tomato was particularly low at the urban garden Growing Home in 2013 and 2014 and at the urban garden Garfield in 2015 (Table 1.2), and these two gardens were characterized by relatively low ozone and high canopy transmittance compared to the peri-urban gardens (Table 1.4). While this does not help explain the driving forces behind yield variability of 'Bush Goliath' tomato, it does illustrate the potential for spurious correlations in observational studies and the importance of careful interpretation of resulting models.

S156 and R123 snap bean cultivars were both negatively influenced by ozone, but the yield of the susceptible cultivar S156 was not reduced relative to the resistant cultivar at the peri-

urban gardens with elevated ozone. Burkey et al., (2005) tested these same snap bean cultivars in open-top chambers and ambient air at gardens with elevated ozone and found that biomass and yield of the ozone susceptible cultivar (S156) was reduced by 30-60%. Similarly, Gregg et al. (2003), found that ozone was the primary cause of a two to five fold reduction in productivity of urban and rural Cottonwood stands in the New York City area. Studies relating food crop production along transects in India (Agrawal et al., 2003), London (Mansfield and Freer-Smith, 1981; Ashmore et al., 1988), and Los Angeles (Middleton et al., 1950) have shown that exposure to industrial pollutants, such as NO_X, SO_2, and ozone reduces yield and that crop damage is greatest within or immediately adjacent to city centers (i.e., peri-urban locations). While the abatement of many of these harmful chemicals has improved through new emission standards and regulation, ozone remains elevated in and around many cities (Fuhrer, 2009). The lack of clear effects of ozone on the bean cultivars suggests that the dynamics of ozone exposure may be as important as aerial concentration.

Carbon dioxide influenced yield of tomato, pepper, beet and Brussels sprout, but the inconsistent direction and magnitude of the relationship suggests that CO_2 was a proxy for other sources of variation such as the UHI or canopy and light measures (Fig. 1.8, 1.9, and 1.11). Free air CO_2 enrichment (FACE) experiments have shown that elevated CO_2 can contribute to slight yield increases in C3 crops, but other factors that limit yield, such as water, light, or competition, are often more important (Long et al., 2006). Increasing carbon fertilization does cause increased dark respiration which can account for greater plant growth in high CO_2 environments, which was evidenced by 1.8 times greater average tomato plant biomass in both cultivars at urban gardens compared to rural gardens in this study (data not shown). Average concentrations of CO_2 was positively correlated to temperature (Fig. 1.11) and negatively correlated to distance to city

center (Fig. 1.8 and 1.9), which may explain the instances of negative CO_2 influence in SEM models (Fig. 1.8 and 1.11).

Elevated CO_2 and temperatures in cities are often similar to those predicted in future climate change scenarios; thus, the urban environment may serve as a natural laboratory for studying the effects of climate change on plants (Ziska et al., 2003; Youngsteadt et al., 2015). Only Brussels sprout was influenced by both temperature and CO_2 latent variables, although the relationship between yield and CO_2 was negative (Fig. 1.11). There was a threefold and a twofold biomass production difference in 2013 and 2014, respectively, between urban and rural gardens, although in 2015 there was no statistical difference in biomass between the gardens (Table 1.2). Ziska et al., (2003) found that the weed *Ambrosia trifida* had a threefold biomass increase over two seasons at an urban garden in Baltimore compared to a rural garden. The magnitude of this growth response between urban and rural locations was most pronounced for Brussels sprout, which suggests that climate change will have a variable effect among crops. As temperature increases in city centers and under climate change, VPD increases will increase urban farming water demand (Johnson et al., 2015). There was higher VPD in the urban gardens (Fig. 1.2-1.4) but the lack of effects on plant production was likely due to the high soil fertility and maintenance of moisture at near field capacity. Distance to city center, which positively influenced tomato yield and negatively influenced pepper yield (Fig. 1.8 and 1.9), was likely a manifestation of unexplained or unmeasured environmental variation in the models. Yield and biomass were not associated in tomato cultivar "Virginia Sweet" ($R^2 = 0.08$, $P = 0.156$) and biomass was 1.8 times higher at urban gardens suggesting fruit set was lower with higher temperatures, which is a known problem in tomatoes (Rudich et al., 1977). Potato aphids (*Macrosiphum euphorbiae* Thomas) and tomato hornworm (*Manduca quinquemaculata*

Haworth) incidence was also greater in tomatoes at urban gardens (data not shown) which may have reduced yields. The hybrid pepper 'Bounty' was negatively influenced by distance to city center suggesting increased yield at urban gardens (Table 1.2). Yield and biomass were positively ($R^2 = 0.23$, $P < 0.001$) correlated for pepper and yields tended to be higher in urban gardens (Table 1.2), but in 2014 in the urban garden Growing Home over half of the 'Bounty' peppers were infected by bacterial soft rot (*Erwinia carotovora ssp. carotovora*) which may have reduced the magnitude of the influence of distance to city center.

Wind speed had a relatively minor effect on yield variability among gardens. Wind speed differences among gardens was substantial (Fig. 1.2, 1.3, and 1.4), but only snap bean yield was negatively influenced by wind (Fig. 1.7). Hodges et al. (2004) found increased yield and biomass of snap beans with reduced wind speed near a windbreak. Measures of stem thickness and height at final harvest were recorded in 2013 and 2014, and all crops had thicker stems and reduced plant height in the rural gardens (data not shown). This suggests wind altered plant growth and architecture, but these changes did not reduce yield of most crops in this study, despite being grown in the "Windy City" of Chicago. Lack of observed differences here may be due in part to the adequate supply of soil moisture provided at each garden, which eliminated the possibility of moisture stress from elevated evapotranspiration.

Tomato, beet, and snap bean yields were influenced by micrometeorological factors that were different among cultivars. Tomato cultivars were most disparate in response to local environment, and differences are likely due to the large genetic variability within tomato, especially with respect to heirloom and hybrid differences (Bai and Lindhout, 2007). Variation within garden beet appears to be less than tomato (de Bock, 1986), but the variation between the two popular cultivars used in this study was enough to elicit differences among gardens. Snap

beans are similarly low in genetic variability (Koenig and Gepts, 1989). Differences between cultivars used in this study indicate that selection and breeding of vegetables in urban environments would improve crop adaptation and yield in cities. Participatory breeding is seen as a means of making selection in multiple environments without extensive investment, especially for less economically important crops and organic systems (Hoagland et al., 2015). Indeed, two ongoing studies in Chicago, IL and Milwaukee, WI have been using a participatory approach to identify the best cultivars and to develop new tomato cultivars for urban farmers (Dawson, 2015; John Taylor personal communication, May 10, 2016).

Conclusion

The purpose of this study was to document micrometeorological and pollution differences across a rural to urban transect and then use that data to explain variability in vegetable yield across the large metropolitan region of Chicago, IL. The factors most strongly driving variability in vegetable crop yield across the Chicago metro region included light, ozone, and temperature. Spring- and fall-planted crops were most influenced by ozone and temperature, whereas differences on yield of summer-planted crops was largely driven by light.

Some crops tested in this study seemed to benefit from the UHI effect. Also, outside of a few easily controllable aphid infestations and a pepper disease at one garden in one year, there was no biotic or abiotic factors that reduced yield or marketability acorss peri-urban or rural sites. Warmer temperatures, nineteen additional frost-free days, and observed yield increases of cool-season crops at urban gardens in this study suggests urban farmers may plant crops earlier in the spring and be the first to market each season. Preliminary economic analysis of data from this study (data not shown) suggests that, despite cases of increased urban yields, snap beans and Brussels sprouts would not be profitable crops for urban farmers because of greater land area

requirements and relatively low market value. Tomatoes will likely the most profitable crop in any environment due to high market value, followed by peppers, kale, and onions (data not shown). If profitability is the primary objective, urban farmers should choose high-yielding and high-value crops (even those that require intensive management) due to scarcity of land and abundance of labor.

With growing excitement about local and urban food production (Mok et al., 2014) and rapid and continued global urbanization (United Nations, 2014), there is demand for increased urban food production. Urban food production is not without its challenges including: land, water, and resource availability, land tenure issues, patchwork policy oversight, soil and air pollution, and unpredictable biotic stresses (Bryld, 2003). However, as this and other studies have shown, there are significant benefits of and opportunities for the growth of urban agriculture (Mok et al. 2013, Wakefield et al., 2007; Opitz et al., 2016).

Tables

		Standard Soil Test							Base Saturation													
	Garden	OM (%)	Total CEC (meq/100 g)	pH	P (mg/kg)	Ca (mg/kg)	Mg (mg/kg)	K (mg/kg)	Na (mg/kg)	Ca (%)	Mg (%)	K (%)	Na (%)	Other Bases (%)	H (%)	NO3-N (ppm)	NH4-N (ppm)	S (ppm)	B (mg/kg)	Fe (mg/kg)	Mn (mg/kg)	Cu (mg/kg)	Zn (mg/kg)
March 2013	Kuipers	13	21.6	8.1	131	2164	656	1720	218	49.9	25.3	20.4	4.4	0	0	28	88						
	St Charles	14	20	8.2	155	2018	615	1555	193	50.3	25.6	19.9	4.2	0	0	15	71						
	Cantigny	10.7	20.2	8	120	2160	588	1360	229	53.5	24.3	17.3	4.9	0	0	23	67						
	Cantata	12.6	19.5	8.2	125	2124	590	1257	175	54.4	25.2	16.5	3.9	0	0	20	43						
	Growing Home	13.8	22.6	8.1	175	2256	711	1727	232	49.7	26.2	19.6	4.5	0	0	32	79						
	Garfield	12.8	20.3	7.9	131	2101	635	1416	195	51.8	26.1	17.9	4.2	0	0	22	47						
March 2015	Kuipers	13.04	10.59	7.6	241	1023	446	397	78	48.3	35.1	9.61	3.2	3.8	0	46.6	1.4	23	1.61	168	6	0.76	2.66
	StCharles	17.29	10.46	7.9	261	1067	427	196	161	51	34.02	4.8	6.69	3.5	0	33.7	1.6	21	1.38	166	5	0.54	2.85
	Cantigny	15.29	10.49	7.5	271	1057	479	181	78	50.38	38.05	4.42	3.23	3.9	0	38.5	1.8	52	1.15	173	7	0.72	5.84
	Cantata	16.27	9.74	7.5	251	1055	424	162	32	54.16	36.28	4.26	1.43	3.9	0	37.6	2.3	22	0.98	163	6	0.67	3.54
	Growing Home	15.65	9.49	7.6	250	1027	391	234	32	54.11	34.33	6.32	1.47	3.8	0	35.7	1.8	23	1.04	168	5	0.51	2.84
	Garfield	12.81	10.01	7.4	241	1116	408	189	34	55.74	33.97	4.84	1.48	4	0	39.8	1.7	24	0.99	167	5	0.72	2.86

		Plant Root Simulator Probes (PRS™)														
	Garden	Pb	Total N	NO3-N	NH4-N	P	K	Ca	Mg	Fe	Mn	Cu	Zn	B	S	Al
July 2014	Kuipers	3.8	54.0	52.7	1.27	47.8	652	1517	481	24.5	2.05	0.58	6.35	0.79	35	10.4
	StCharles	4.2	39.2	37.8	1.43	39.6	296	1767	528	19.4	1.57	0.44	5.80	0.88	74	14.5
	Cantigny	3.4	70.4	68.7	1.63	9.5	326	1759	570	36.6	1.12	0.52	7.62	0.80	1137	13.2
	Cantata	5.5	105.4	104.4	1.00	39.7	918	1640	491	26.8	1.80	0.48	7.11	1.02	168	13.2
	Growing Home	10.0	87.7	86.1	1.61	59.5	857	1621	464	47.2	2.26	0.87	13.42	0.92	258	8.7
	Garfield	6.7	168.3	167.2	1.11	59.6	401	2289	561	31.7	2.62	0.91	9.48	0.75	315	12.4
May 2015	Kuipers	6.8	197.8	195.4	2.45	67.8	79	2363	585	23.8	1.20	0.60	11.91	1.60	49	11.3
	St Charles	7.8	249.7	247.0	2.73	73.9	79	2439	561	32.6	1.54	0.80	12.87	1.67	111	11.8
	Cantigny	0.9	83.0	80.7	2.27	20.5	29	2084	613	15.2	0.30	0.40	7.11	1.28	1059	11.6
	Cantata	5.2	195.8	193.6	2.25	63.5	46	2727	576	23.0	1.38	0.59	9.67	1.04	170	11.7
	Growing Home	5.4	116.1	113.6	2.53	57.0	28	2431	529	25.2	0.92	0.62	8.66	1.86	633	13.7
	Garfield	9.0	175.0	172.5	2.45	73.8	48	2648	518	46.2	1.68	0.96	15.31	1.07	184	10.6
Sept 2015	Kuipers	6.3	206.7	204.9	1.78	44.2	116	2299	607	21.9	1.60	0.48	9.31	1.01	54	9.2
	StCharles	9.7	253.8	251.7	2.14	54.6	72	2307	507	25.6	1.83	0.63	12.86	0.72	146	8.4
	Cantigny	2.3	80.0	78.4	1.67	8.5	36	1933	631	25.3	1.19	0.44	8.65	0.50	840	7.8
	Cantata	7.0	250.5	248.8	1.77	50.2	43	2520	525	54.3	2.42	0.66	10.78	0.65	211	8.5
	Growing Home	6.2	116.5	114.9	1.57	43.9	49	2538	503	27.0	1.61	0.57	9.66	0.64	191	9.3
	Garfield	4.7	82.2	81.0	1.15	40.7	33	2641	535	25.1	1.55	0.94	8.19	0.84	197	10.3

Table 1.1 Standard soil test and PRS™ probe readings from six test gardens in the greater Chicago, IL metro region. Standard soil test were done at Midwest Lab Inc. (Omaha, NE). The March 2013 test was taken from random in the bulk piles before raised bed gardens were filled. March 2015 tests were 6 inch soil cores taken from 16 random raised beds from each site. Plant root simulator probes are a positive and negative probe with a membrane that acts as a root surface and was inserted into the soil for a two week period. The probes were then analyzed at Western Ag Inc. (Saskatoon, SK). Units expressed are µg solute per 10 cm2 probe membrane per time of burial (14 days). These units are not comparable to units of standard soil tests, but are useful for comparison between sites.

		Kale		Onion		Pepper		Tomato		Bean		Beet		Brussels Sprout	
		Winterbor	*Toscano*	*Candy*	*Red Zeppelin*	*Antohi Rom.*	*Bounty*	*Bush Goliath*	*Virginia Sweet*	*R123*	*S156*	*Merlin*	*Chioggia*	*Diablo*	*Long Island*
2013	Kuipers	3.64^{b}		0.62^{a}		2.15^{a}	2.93^{a}	4.29^{c}	4.28^{bc}	1.46^{a}	0.74^{b}	0.16^{a}		1.05^{c}	
	St Charles	3.89^{ab}		0.55^{ab}		1.49^{ab}	2.92^{a}	8.18^{ab}	7.36^{ab}	1.19^{ab}	1.33^{a}	0.15^{a}		1.47^{bc}	
	Cantigny	2.82^{c}		0.37^{c}		1.87^{ab}	1.97^{ab}	6.69^{bc}	7.68^{a}	1.08^{abc}	0.86^{ab}	0.23^{a}		1.59^{bc}	
	Cantata	2.72^{c}		0.40^{c}		1.21^{b}	1.21^{b}	5.26^{bc}	5.07^{abc}	0.67^{c}	0.97^{ab}	0.20^{a}		2.23^{ab}	
	Growing Home	3.86^{ab}		0.56^{ab}		2.03^{a}	2.20^{ab}	4.66^{c}	1.88^{c}	1.05^{abc}	1.06^{ab}	0.12^{a}		1.48^{bc}	
	Garfield	4.41^{a}		0.49^{bc}		2.12^{a}	3.21^{a}	10.53^{a}	5.68^{ab}	0.85^{bc}	1.10^{ab}	0.15^{a}		2.99^{a}	
2014	Kuipers	2.24^{c}	1.08^{c}	0.27^{b}	0.29^{b}	2.78^{ab}	4.38^{ab}	6.14^{ab}	4.07^{bc}	1.24^{c}	1.59^{b}	0.26^{ab}	0.37^{a}	0.78^{b}	0.75^{a}
	St Charles	3.49^{b}	1.39^{b}	0.25^{b}	0.30^{b}	3.05^{ab}	4.78^{ab}	7.08^{a}	7.26^{a}	2.18^{a}	2.23^{b}	0.14^{c}	0.24^{bc}	0.30^{b}	0.12^{c}
	Cantigny	3.04^{b}	1.83^{b}	0.24^{b}	0.24^{b}	3.36^{a}	5.16^{a}	5.67^{abc}	4.78^{b}	1.76^{abc}	1.90^{b}	0.21^{bc}	0.29^{ab}	0.76^{b}	0.26^{bc}
	Cantata	3.36^{b}	2.58^{a}	0.24^{b}	0.25^{b}	2.61^{ab}	3.64^{bc}	4.91^{bc}	4.54^{b}	2.11^{ab}	2.31^{b}	0.15^{c}	0.18^{c}	0.29^{b}	0.15^{c}
	Growing Home	3.67^{b}	2.54^{a}	0.30^{b}	0.30^{b}	2.27^{b}	2.51^{c}	3.66^{c}	1.75^{c}	1.64^{bc}	1.901	0.28^{ab}	0.37^{a}	0.78^{b}	0.73^{ab}
	Garfield	4.55^{a}	2.62^{a}	0.44^{a}	0.40^{a}	3.47^{a}	4.93^{ab}	5.34^{abc}	4.28^{b}	2.20^{a}	3.27^{a}	0.32^{a}	0.37^{a}	1.42^{a}	1.03^{a}
2015	Kuipers	2.37^{bc}	1.34^{bc}	0.24^{bc}	0.25^{ab}	1.88^{ab}	2.93^{ab}	3.76^{ab}	7.80^{a}	1.33^{ab}	1.09^{bc}	0.43^{ab}	0.5^{a}	3.452	1.88^{b}
	St Charles	3.32^{a}	1.95^{a}	0.20^{cd}	0.23^{abc}	1.98^{ab}	3.17^{ab}	3.78^{ab}	8.30^{a}	1.80^{a}	1.63^{a}	0.46^{a}	0.58^{a}	7.71^{a}	4.40^{a}
	Cantigny	2.52^{b}	1.68^{ab}	0.17^{d}	0.18^{bc}	1.49^{abc}	2.26^{bc}	3.26^{ab}	7.45^{ab}	1.16^{b}	1.30^{abc}	0.30^{c}	0.62^{a}	3.39^{b}	2.49^{b}
	Cantata	1.79^{c}	1.21^{c}	0.19^{cd}	0.17^{c}	1.11^{c}	1.65^{c}	4.07^{a}	5.31^{b}	0.59^{c}	0.60^{d}	0.26^{c}	0.16^{b}	4.07^{b}	2.38^{b}
	Growing Home	2.66^{ab}	1.75^{ab}	0.28^{ab}	0.27^{a}	2.06^{a}	3.47^{a}	3.38^{ab}	7.77^{a}	1.73^{a}	1.38^{ab}	0.34^{bc}	0.52^{a}	3.35^{b}	2.18^{b}
	Garfield	2.54^{b}	1.79^{a}	0.31^{a}	0.23^{abc}	1.42^{bc}	2.36^{bc}	2.76^{b}	6.49^{ab}	1.01^{bc}	0.90^{cd}	0.46^{a}	0.54^{a}	4.86^{b}	4.25^{a}

Table 1.2 Yields of crops and cultivars across three years from six test gardens across the Chicago, IL metro region. Sites within each year are arranged from top to bottom according to distance to city center (rural to urban cline). Yield data are presented as harvested g/plot, except beets and onions which are fresh g/plant and Brussels sprouts which are total biomass/plot. Missing cultivars in 2013 were not planted in the first year of the study. Means were separated by variety within site within year from linear mixed model estimates and using the LSD means separation method. Interactions of variety, site, and year were significant across most crops. Cultivars 'Winterbor', 'Candy', 'Red Zephlin', 'Bush Goliath', 'Merlin', and 'Diablo' are hybrids and 'Toscano', 'Antohi Romanian', 'Virginia Sweet', 'Chioggia', and 'Long Island' are heirlooms.

Crop	Variety	Model χ^2	Test Stat	k	AIC	BIC	CFI	RMSEA	SRMR	Variety χ^2	R^2
Kale	Winterbor	0.87^{ns}	1.25	4	212	263	1.00	0.00	0.01	0.02	0.76 ***
	Toscano									1.06	0.95 **
Onion	Candy	0.82^{ns}	1.55	4	256	298	1.00	0.00	0.01	0.21	0.61 **
	Red Zephlin									1.34	0.85 *
Tomato	Bush Goliath	0.37^{ns}	6.47	6	510	586	0.99	0.07	0.01	2.35	0.67 **
	Virginia Sweet									4.12	0.35 **
Pepper	Anthoni Romanian	0.97^{ns}	0.51	4	333	390	1.00	0.00	0.00	0.23	0.84 ***
	Bounty									0.28	0.55 **
Bean	Resistant	0.30^{ns}	4.84	4	323	381	0.99	0.11	0.06	3.22	0.71 **
	Susceptible									1.63	0.52 *
Beet	Chioggia	0.95^{ns}	0.69	4	348	398	1.00	0.00	0.02	0.20	0.34***
	Merlin									0.48	0.88 **
Brussels	Diablo	0.89^{ns}	0.25	2	208	244	1.00	0.00	0.00	0.19	0.50 **
Sprout	Long Island									0.06	0.95 **

Table 1.3 Fit statistics for structural equation models for each crop and variety. Model χ^2 is the model test of the baseline model, k is degrees of freedom of the model, AIC and BIC are Akaike weights and Bayesian weights, respectively. CFI is comparative fit index scaled from 0-1 with 1 being the best fit. RMSEA is the root mean square error of approximation on a scale from 0-1 with 0 being the best fit. SRMR is standardized root mean square residual on a scale of 0-1 with 0 being the best fit. Variety χ^2 is the proportion of the model χ^2 taken up by each variety. R^2 is the total variation within variety accounted for by the model. ns represents non-significance, * is significance at the 0.05 level, ** is significance at the 0.01 level, and *** is significance at the 0.001 level.

	Location	GDD (10°C)	GDD (4°C)	Last Frost	First Frost	Frost Free Days	Leaf Area	Transmission Coefficient	Radiant Exposure	Sun Hours	SUM06	AOT40	Distance to City
2013	Kuipers	1460	2300	21-Apr	21-Oct	183	0.07	0.96	3160	1400	640	42000	77.5
	St Charles	1450	2280	21-Apr	21-Oct	183	0.19	0.91	3120	1440			60.9
	Cantigny	1510	2360	21-Apr	21-Oct	183	0.38	0.72	2880	1210	2050	105200	43.5
	Cantata	1570	2420	20-Apr	22-Oct	185	0.77	0.57	2780	1080			18.2
	Growing Home	1700	2580	20-Apr	25-Oct	188	0.25	0.88	2710	1240			11.2
	Garfield	1680	2470	4-Apr	25-Oct	204	0.03	0.98	2920	1240	450	29000	7.5
2014	Kuipers	1550	2540	16-Apr	30-Oct	197	0.07	0.96	3800	1620	830	60300	77.5
	St Charles	1600	2590	16-Apr	19-Oct	186	0.19	0.91	3800	1610			60.9
	Cantigny	1640	2640	16-Apr	19-Oct	186	0.38	0.72	3570	1460	1000	51200	43.5
	Cantata	1650	2660	16-Apr	19-Oct	186	0.77	0.57	3440	1320			18.2
	Growing Home	1720	2740	16-Apr	1-Nov	199	0.25	0.88	3600	1510			11.2
	Garfield	1790	2830	15-Apr	2-Nov	201	0.03	0.98	3580	1470	680	37000	7.5
2015	Kuipers	1690	2750	24-Apr	17-Oct	176	0.07	0.96	3830	1410	30	2100	77.5
	St Charles	1720	2770	24-Apr	17-Oct	176	0.19	0.91	3660	1360	90	6350	60.9
	Cantigny	1730	2790	24-Apr	17-Oct	176	0.38	0.72	3360	1240	160	9700	43.5
	Cantata	1780	2850	24-Apr	18-Oct	177	0.77	0.57	3240	1190	690	40000	18.2
	Growing Home	1730	2810	23-Apr	8-Nov	199	0.25	0.88	3460	1300	3	270	11.2
	Garfield	1890	2980	4-Apr	14-Nov	224	0.03	0.98	3460	1290	40	2450	7.5

Table 1.4 Accumulated measures calculated from environmental data collected at each of six sites across the Chicago, IL metro region. GDD is growing degree days with base temperature indicated. Last and first frost are the dates of last spring frost and first fall frost respectively. Frost free days is the total days between the last and first frost. Leaf area is the leaf are index and transmission coefficient is canopy transmission coefficient both taken from fish eye photo analysis. Radiant exposure is the integration of the light irradiance measures in $kW \bullet m^{-3}$. Sun hours is a measure of total daytime (0500 to 1900) hours where solar radiation is above 65% of maximum radiation. SUM06 is the sum of all hours with ozone above 0.06 ppm. AOT40 is sum of part per billion hourly ozone average minus 40 if ozone average is over 40 ppb (Σ(ppb h – 40)). The Distance to city is a measure from the same point in downtown Chicago to each site in km.

Model	Test Stat	Model χ^2	k	CFI	AIC	BIC	RMSEA	SRMR	Variety	Variety χ^2	R^2
yield~(ozone_d+sum06)+co2+gdd4+(trcoef+slrj+solar_d)+vpd	94.092	0	32	0.798	572.049	678.54	0.360***	0.161	WinterBor Toscano	40.452 53.64	0.669*** 0.901*
yield~sum06+co2+gdd4+(slrj+slrj_d)+vpd	28.756	0	8	0.911	418.045	504.919	0.416**	0.053	WinterBor Toscano	24.244 4.512	0.666*** 0.919**
yield~heat+sum06+slrj	20.288	0	4	0.897	277.896	328.34	0.521**	0.091	WinterBor Toscano	8.619 11.669	0.318** 0.731**
yield~gdd4+sum06+(trcoef+lai)+dist_cc	1.994	0.92	6	1	410.587	477.844	0 ns	0.01	WinterBor Toscano	1.461 0.534	0.652** 0.899**
yield~gdd4+ozone_d+(trcoef+lai)+dist_cc	1.874	0.931	6	1	416.359	483.616	0 ns	0.012	WinterBor Toscano	1.475 0.398	0.645** 0.884**
yield~gdd4+ozone_d+(trcoef+lai)+gps_n	1.987	0.921	6	1	399.865	467.123	0 ns	0.011	WinterBor Toscano	1.67 0.316	0.589** 0.846***
yield~gdd4+ozone_d+(trcoef+lai)+vpd_d	4.834	0.565	6	1	389.928	457.185	0 ns	0.022	WinterBor Toscano	2.657 2.177	0.766** 0.862***
yield~temp_n+ozone_d+(trcoef+lai)+vpd_d	5.577	0.472	6	1	389.893	457.151	0 ns	0.019	WinterBor Toscano	3.469 2.107	0.747** 0.901**
yield~gdd4+ozone_d+(trcoef+lai)	3.476	0.481	4	1	312.471	362.914	0 ns	0.009	WinterBor Toscano	3.168 0.308	0.760* 0.843**
yield~(gdd4+gdd10)+ozone_d+solar_d	4.005	0.399	4	1	235.8	286.243	0 ns	0.019	WinterBor Toscano	1.269 2.786	0.765** 0.859**
yield~(gdd4+gdd10)+ozone_d+slrj_d	8.106	0.088	4	0.984	203.297	253.74	0.262ns	0.01	WinterBor Toscano	5.748 2.358	0.747*** 0.847***
yield~temp_d+ozone_d+(trcoef+lai)	1.835	0.766	4	1	304.277	354.277	0 ns	0.007	WinterBor Toscano	1.045 0.789	0.622*** 0.823**
yield~gdd4+sum06+(trcoef+lai)	1.7	0.791	4	1	309.375	359.818	0 ns	0.009	WinterBor Toscano	1.33 0.369	0.798** 0.871**
yield~gdd4+aot40+(trcoef+lai)	3.35	0.501	4	1	307.357	357.8	0 ns	0.026	WinterBor Toscano	2.862 0.488	0.777* 0.926*
yield~gdd4+aot40+trcoef+(slrj_d+slrj)	7.099	0.312	6	0.995	301.797	369.055	0.11 ns	0.027	WinterBor Toscano	0.796 6.303	0.780** 0.952**
yield~gdd4+aot40+(slrj_d+slrj)	**1.253**	**0.869**	**4**	**1**	**212.378**	**262.822**	**0 ns**	**0.011**	**WinterBor** **Toscano**	**0.192** **1.061**	**0.755*** **0.949****

Table 1.5 Kale cultivars structural equation model selection test statistics. Models were run in lavaan package in R. Bolded model is the selected model used in the paper. Model parameters outside of parenthesis are manifest variable and parameters inside of parenthesis represent a latent variable. Model parameters are defined as followed; *slrj* is the total radiant exposure and *slrj_d* is the daytime radiant exposure, *dist_cc* is the distance to the city center from each garden, *trcoef* is the canopy transmission coefficient, and *lai* is the canopy light area index. All other model parameters are defined in the text. Model χ^2 is the model test of the baseline model, k is degrees of freedom of the model, AIC and BIC are Akaike weights and Bayesian weights, respectively. CFI is comparative fit index scaled from 0-1 with 1 being the best fit. RMSEA is the root mean square error of approximation on a scale from 0-1 with 0 being the best fit. SRMR is standardized root mean square residual on a scale of 0-1 with 0 being the best fit. Variety χ^2 is the proportion of the model χ^2 taken up by each variety. R^2 is the total variation within variety accounted for by the model. ns represents non-significance, * is significance at the 0.05 level, ** is significance at the 0.01 level, and *** is significance at the 0.001 level.

Model	Test Stat	Model χ^2	k	CFI	AIC	BIC	RMSEA	SRMR	Variety	Variety χ^2	R^2
yield~sum06+co2+temp_d+gdd4	0.835	0.659	2	1	425.797	487.056	0 ns	0.009	Candy	0.073	0.638**
									Red Zephlin	0.761	0.865***
yield~sum06+temp_d+gdd4	0.655	0.721	2	1	344	388.766	0 ns	0.013	Candy	0.499	0.604***
									Red Zephlin	0.156	0.848***
yield~ozone_d+solar_d+gdd4	2.808	0.246	2	0.979	354.544	399.31	0.184 ns	0.031	Candy	0.367	0.580**
									Red Zephlin	2.441	0.821*
yield~sum06d+solar_d+gdd4	9.385	0.009	2	0.846	352.73	397.497	0.555*	0.06	Candy	2.943	0.515**
									Red Zephlin	6.442	0.743*
yield~sum06+(solar_d+slrj_d)+gdd4	11.389	0.181	8	0.974	345.9	400.09	0.188 ns	0.087	Candy	6.94	0.48*
									Red Zephlin	4.449	0.791**
yield~ozone_d+(solar_d+slrj_d)+gdd4	12.247	0.141	8	0.965	353.736	407.927	0.210 ns	0.106	Candy	8.006	0.533**
									Red Zephlin	4.24	0.820**
yield~ozone_d+(trcoef+lai)+gdd4	**1.549**	**0.818**	**4**	**1**	**255.945**	**298.355**	**0 ns**	**0.006**	Candy	**0.212**	**0.607****
									Red Zephlin	**1.337**	**0.849***
yield~ozone_d+(trcoef+lai)+temp_n+gdd4	1.949	0.924	6	1	332.895	389.442	0 ns	0.008	Candy	0.254	0.761*
									Red Zephlin	1.694	0.849*
yield~ozone_d+(trcoef+lai)+temp_n+gdd10	1.733	0.785	4	1	256.738	299.148	0 ns	0.006	Candy	0.268	0.601***
									Red Zephlin	1.465	0.843*
yield~ozone_d+(trcoef+lai)+temp_n	0.397	0.983	4	1	282.833	325.243	0 ns	0.008	Candy	0.148	0.637*
									Red Zephlin	0.249	0.660**
yield~sum06+(trcoef+lai)+temp_n	1.009	0.908	4	1	280.249	322.659	0 ns	0.008	Candy	0.397	0.729**
									Red Zephlin	0.612	0.71*
yield~sum06+(trcoef+lai)+gdd4	2.229	0.694	1	1	270.284	312.694	0 ns	0.01	Candy	0.695	0.612***
									Red Zephlin	1.534	0.838*
yield~ozone_d+(trcoef+lai)+gdd4+vpd_d	7.835	0.25	6	0.989	315.916	372.463	0.160 ns	0.013	Candy	3.167	0.746*
									Red Zephlin	4.668	0.883*
yield~ozone_d+(trcoef+lai)+gdd4+dist_cc	3.423	0.754	6	1	318.864	375.41	0 ns	0.011	Candy	0.859	0.911**
									Red Zephlin	2.564	0.863*

Table 1.6 Onion cultivars structural equation model selection test statistics. Models were run in lavaan package in R. Bolded model is the selected model used in the paper. Model parameters outside of parenthesis are manifest variable and parameters inside of parenthesis represent a latent variable. Model parameters are defined as followed; ; *vpd_d* is the vapor pressure deficit during the daytime, *solar_d* is the daytime average light radiance and *slrj_d* is the daytime radiant exposure, *dist_cc* is the distance to the city center from each garden, *trcoef* is the canopy transmission coefficient, and *lai* is the canopy light area index. All other model parameters are defined in the text. Model χ^2 is the model test of the baseline model, k is degrees of freedom of the model, AIC and BIC are Akaike weights and Bayesian weights, respectively. CFI is comparative fit index scaled from 0-1 with 1 being the best fit. RMSEA is the root mean square error of approximation on a scale from 0-1 with 0 being the best fit. SRMR is standardized root mean square residual on a scale of 0-1 with 0 being the best fit. Variety χ^2 is the proportion of the model χ^2 taken up by each variety. R^2 is the total variation within variety accounted for by the model. ns represents non-significance, * is significance at the 0.05 level, ** is significance at the 0.01 level, and *** is significance at the 0.001 level.

Model	Test Stat	Model χ^2	k	CFI	AIC	BIC	RMSEA	SRMR	Variety	Variety χ^2	R^2
yield~ozone+gdd10+(trcoef+lai)+co2	0.856	0.931	4	1	552.665	631.841	0 ns	0.12	R123	0.427	0.397**
									S156	0.428	0**
yield~ozone+gdd10+(solar_d+solarmax_d)+co2	13.689	0.033	6	0.889	615.839	691.848	0.267*	0.072	R123	7.252	0.683**
									S156	6.436	0.449*
yield~ozone+gdd10+(wind_d+windmax_d)+co2	3.487	0.746	6	1	591.292	667.301	0 ns	0.046	R123	1.288	0.440***
									S156	2.199	0***
yield~ozone+temp_d+(wind_d+windmax_d)+co2	3.191	0.785	6	1	575.907	561.916	0 ns	0.046	R123	1.104	0.436***
									S156	2.087	0**
yield~ozone+(wind_d+windmax_d)+co2	2.958	0.565	4	1	473.736	530.743	0 ns	0.05	R123	0.955	0.427***
									S156	2.003	0**
yield~ozone+(wind_d+wind_n)+co2	6.904	0.141	4	0.977	438.018	495.025	0.201 ns	0.076	R123	4.199	0.406***
									S156	2.704	0*
yield~ozone_d+(wind+wind_d)+slrj_d	5.064	0.281	4	0.993	397.482	454.488	0.122 ns	0.045	R123	3.504	0.434***
									S156	1.56	0*
yield~ozone_d+slrj+(wind+wind_d)+temp_d	8.77	0.187	6	0.989	417.857	493.866	0.16 ns	0.067	R123	4.798	0.701**
									S156	3.972	0.477*
yield~ozone_d+slrj+(wind+wind_d)+temp_n	16.4	0.012	6	0.964	398.766	474.775	0.310*	0.114	R123	6.877	0.707**
									S156	9.523	0.495**
yield~ozone_d+slrj+(wind+wind_d)+gdd10	9.798	0.133	6	0.968	410.416	486.425	0.188 ns	0.076	R123	4.866	0.701**
									S156	4.932	0.510**
yield~ozone_d+slrj+(wind+wind_d)	**4.842**	**0.304**	**4**	**0.996**	**323.859**	**380.866**	**0.108 ns**	**0.057**	R123	**3.216**	**0.704****
									S156	**1.626**	**0.521***
yield~ozone_d+solar_d+(wind+wind_d)	5.047	0.283	4	0.996	307.596	364.6	0.121 ns	0.045	R123	3.489	0.647***
									S156	1.558	0.197 ns
yield~sum06+solar+(wind+wind_d)	4.204	0.379	4	0.999	294.537	351.544	0.053 ns	0.051	R123	2.618	0.513***
									S156	1.586	0.086*
yield~co2_n+solar+(wind+wind_d)	6.27	0.18	4	0.988	372.196	429.203	0.178 ns	0.069	R123	3.377	0.491***
									S156	2.893	0.078*
yield~gdd10+solar+(wind+wind_d)	6.568	0.161	4	0.988	347.781	404.788	0.189 ns	0.072	R123	3.014	0.489***
									S156	3.55	0.083**
yield~ozone_d+(trcoef+lai)+(wind+wind_d)	9.33	0.501	10	1	318.932	388.607	0 ns	0.058	R123	6.277	0.416**
									S156	3.053	0*

Table 1.7 Snap bean cultivars structural equation model selection test statistics. Models were run in lavaan package in R. Bolded model is the selected model used in the paper. Model parameters outside of parenthesis are manifest variable and parameters inside of a parenthesis represent a latent variable. Model parameters are defined as followed; *solar_d* is the daytime average light radiance and *slrj_d* is the daytime radiant exposure, *dist_cc* is the distance to the city center from each garden, *temp_d* and *temp_n* are the average temperature in the daytime and nighttime respectively, *wind, wind_d,* and *windmax_d* are the average wind speed, daytime average wind speed, and average daytime hourly maximum wind speed respectively, and *trcoef* and *lai* are the canopy transmission coefficient and canopy light area index respectively. All other model parameters are defined in the text. Model χ^2 is the model test of the baseline model, k is degrees of freedom of the model, AIC and BIC are Akaike weights and Bayesian weights, respectively. CFI is comparative fit index scaled from 0-1 with 1 being the best fit. RMSEA is the root mean square error of approximation on a scale from 0-1 with 0 being the best fit. SRMR is standardized root mean square residual on a scale of 0-1 with 0 being the best fit. Variety χ^2 is the proportion of the model χ^2 taken up by each variety. R^2 is the total variation within variety accounted for by the model. ns represents non-significance, * is significance at the 0.05 level, ** is significance at the 0.01 level, and *** is significance at the 0.001 level.

Model	Test Stat	Model χ^2	k	CFI	AIC	BIC	RMSEA	SRMR	Variety	Variety χ^2	R^2
yield~ozone+co2_d+(slrj_d+solarmax_d)+gps_w	12.968	0.044	6	0.946	544.942	620.951	0.254*	0.53	Antohi Rom.	6.825	0.815***
									Bounty	6.143	0.558*
yield~co2_d+(slrj_d+solarmax_d)+gps_w	2.27	0.686	4	1	422.568	479.575	0 ns	0.021	Antohi Rom.	1.083	0.818***
									Bounty	1.188	0.542**
yield~co2_d+(trcoef+lai)+gps_w	2.168	0.705	4	1	413.622	470.628	0 ns	0.033	Antohi Rom.	0.864	0.654**
									Bounty	1.304	0.075***
yield~co2_d+(slrj_d+solarmax_d)+dist_cc	2.155	0.707	4	1	422.167	179.173	0 ns	0.02	Antohi Rom.	1.045	0.818***
									Bounty	1.111	0.549**
yield~co2_d+(slrj_d+solarmax_d+trcoef)+dist_cc	4.214	0.979	12	1	532.005	598.513	0 ns	0.033	Antohi Rom.	1.893	0.833**
									Bounty	2.348	0.550*
yield~co2_d+slrj_d+(dist_cc+gps_w)	0.662	0.956	4	1	320.094	377.101	0 ns	0.003	Antohi Rom.	0.338	0.840***
									Bounty	0.324	0.550**
yield~co2_d+(slrj_d+solar_d)+(dist_cc+gps_w)	6.446	0.777	10	1	410.653	480.328	0 ns	0.049	Antohi Rom.	2.551	0.909 ns
									Bounty	3.895	0.628 ns
yield~co2_d+(slrj_d+solarmax_d)+(dist_cc+gps_w)	3.174	0.977	10	1	364.104	433.778	0 ns	0.018	Antohi Rom.	1.567	0.828***
									Bounty	1.607	0.550**
yield~co2_d+(slrj_d+solarmax_d+trcoef)+(dist_cc+gps_w)	7.472	0.995	20	1	473.534	552.71	0 ns	0.031	Antohi Rom.	3.371	0.824***
									Bounty	4.101	0.559**
yield~co2+slrj_d+(dist_cc+gps_w)	**0.51**	**0.972**	**4**	**1**	**333.41**	**390.417**	**0 ns**	**0.002**	Antohi Rom.	**0.228**	**0.828*** **
									Bounty	**0.282**	**0.544****
yield~co2_n+slrj_d+(dist_cc+gps_w)	0.502	0.973	4	1	342.527	399.534	0 ns	0.002	Antohi Rom.	0.178	0.819***
									Bounty	0.325	0.545**
yield~co2_d+solarmax_d+(dist_cc+gps_w)	0.365	0.985	4	1	333.177	390.183	0 ns	0.004	Antohi Rom.	0.127	0.766***
									Bounty	0.238	0.477***
yield~co2_d+slrj_d+(dist_cc+gps_w)+vpd_d	2.558	0.862	6	1	415.612	491.621	0 ns	0.002	Antohi Rom.	1.193	0.842***
									Bounty	1.365	0.549**
yield~co2_d+slrj_d+(dist_cc+gps_w)+gdd10	0.732	0.994	6	1	404.135	480.144	0 ns	0.002	Antohi Rom.	0.386	0.850***
									Bounty	0.345	0.558**
yield~co2_d+slrj_d+(dist_cc+gps_w)+gdd4	0.746	0.993	6	1	395.852	471.86	0 ns	0.002	Antohi Rom.	0.344	0.851***
									Bounty	0.402	0.564**

Table 1.8 Pepper cultivars structural equation model selection test statistics. Bolded model is the selected model used in the paper. Model parameters outside of parenthesis are manifest variable and parameters inside of a parenthesis represent a latent variable. Model parameters are defined as followed; *solar_d* and *solarmax_d* are the daytime average light radiance and daytime hourly maximal light radiance, *slrj_d* is the daytime radiant exposure, *dist_cc* and *gps_w* are the distance to the city center and the gps west coordinate of each garden respectively, *temp_d* and *temp_n* are the average temperature in the daytime and nighttime respectively, and *trcoef* and *lai* are the canopy transmission coefficient and canopy light area index respectively. All other model parameters are defined in the text. Model χ^2 is the model test of the baseline model, k is degrees of freedom of the model, AIC and BIC are Akaike weights and Bayesian weights, respectively. CFI is comparative fit index scaled from 0-1 with 1 being the best fit. RMSEA is the root mean square error of approximation on a scale from 0-1 with 0 being the best fit. SRMR is standardized root mean square residual on a scale of 0-1 with 0 being the best fit. Variety χ^2 is the proportion of the model χ^2 taken up by each variety. R^2 is the total variation within variety accounted for by the model. ns represents non-significance, * is significance at the 0.05 level, ** is significance at the 0.01 level, and *** is significance at the 0.001 level.

Model	Test Stat	Model χ^2	k	CFI	AIC	BIC	RMSEA	SRMR	Variety	Variety χ^2	R^2
ozone_d+co2_d+(vpd_d+temp_d+gdd10)+(trcoef+lai+slrj_d)	136.249	0	40	0.684	805	913.4	0.366**	0.209	Bush Goliath	57.604	0.552**
									Virginia Sweet	78.646	0.296***
ozone+co2_d+(vpd_d+temp_d+gdd10)+trcoef	35.956	0.003	16	0.829	692.815	778.325	0.263*	0.096	Bush Goliath	10.143	0.639*
									Virginia Sweet	25.813	0.238***
ozone+co2_d+(vpd_d+temp_d)+trcoef+dist_cc	11.045	0.199	8	0.976	673.175	771.354	0.145*	0.064	Bush Goliath	4.942	0.653**
									Virginia Sweet	6.103	0.395**
ozone+co2_d+(trcoef+LAI)+dist_cc	**6.466**	**0.373**	**6**	**0.997**	**509.966**	**585.975**	**0.066 ns**	**0.012**	**Bush Goliath**	**2.351**	**0.668****
									Virginia Sweet	**4.115**	**0.353****
ozone_d+co2_d+(trcoef+LAI)+dist_cc	6.033	0.42	6	1	520.249	596.257	0.017 ns	0.018	Bush Goliath	2.149	0.551**
									Virginia Sweet	3.884	0.354**
ozone_d+co2+(trcoef+lai)+dist_cc	3.755	0.71	6	1	529.52	605.529	0 ns	0.018	Bush Goliath	1.422	0.556**
									Virginia Sweet	2.333	0.347**
ozone_d+co2_d+(solar_d+solarmax_d)+dist_cc	16.013	0.013	6	0.796	639.09	715.099	0.305*	0.11	Bush Goliath	8.202	0.518 ns
									Virginia Sweet	7.849	0.413*
ozone_d+co2_d+(solar_d+solarmax_d)+dist_cc+wind_d	9.65	0.29	8	0.992	595.587	693.766	0.107 ns	0.021	Bush Goliath	4.465	0.557***
									Virginia Sweet	5.185	0.464**
ozone_d+co2_d+(trcoef+lai)+dist_cc+gdd_10	4.825	0.776	8	1	629.051	727.23	0 ns	0.1	Bush Goliath	1.797	0.674**
									Virginia Sweet	3.028	0.343**
ozone_d+co2_d+(trcoef+lai)+dist_cc+vpd_d	6.108	0.635	8	1	611.28	709.779	0 ns	0.011	Bush Goliath	2.68	0.692**
									Virginia Sweet	3.427	0.424**
ozone_d+co2_d+(trcoef+lai)+rh	9.248	0.16	6	0.979	528.232	604.241	0.173 ns	0.014	Bush Goliath	4.507	0.668*
									Virginia Sweet	4.741	0.334**
co2_d+(trcoef+lai)+dist_cc	1.175	0.882	4	1	423.846	480.852	0 ns	0.037	Bush Goliath	0.419	0.08*
									Virginia Sweet	0.756	0.36**

Table 1.9 Tomato cultivars structural equation model selection test statistics. Bolded model is the selected model used in the paper. Model parameters outside of parenthesis are manifest variable and parameters inside of a parenthesis represent a latent variable. Model parameters are defined as followed; *vpd_d* is the daytime vapor pressure deficite average, *solar_d* and *solarmax_d* are the daytime average light radiance and daytime hourly maximal light radiance, *slrj_d* is the daytime radiant exposure, *dist_cc* and *gps_w* are the distance to the city center and the gps west coordinate of each garden respectively, *temp_d* and *temp_n* are the average temperature in the daytime and nighttime respectively, and *trcoef* and *lai* are the canopy transmission coefficient and canopy light area index respectively. All other model parameters are defined in the text. Model χ^2 is the model test of the baseline model, k is degrees of freedom of the model, AIC and BIC are Akaike weights and Bayesian weights, respectively. CFI is comparative fit index scaled from 0-1 with 1 being the best fit. RMSEA is the root mean square error of approximation on a scale from 0-1 with 0 being the best fit. SRMR is standardized root mean square residual on a scale of 0-1 with 0 being the best fit. Variety χ^2 is the proportion of the model χ^2 taken up by each variety. R^2 is the total variation within variety accounted for by the model. ns represents non-significance, * is significance at the 0.05 level, ** is significance at the 0.01 level, and *** is significance at the 0.001 level.

Model	Test Stat	Model χ^2	k	CFI	AIC	BIC	RMSEA	SRMR	Variety	Variety χ^2	R^2
yield~(ozone+ozone_d)+co2_d+gdd4+(slrj_d+solar_d)+gps_w	37.314	0.005	18	0.934	486.605	584.689	0.267**	0.062	Chioggia	17.445	0.444*
									Merlin	19.869	0.976**
yield~(ozone+ozone_d+sum06)s+co2_d+gdd4	14.863	0.249	12	0.982	372.804	431.654	0.126 ns	0.06	Chioggia	10.889	0.497**
									Merlin	3.974	0.865**
yield~(ozone_d+sum06)s+co2_d+gdd4	2.126	0.713	4	1	368.87	419.313	0 ns	0.047	Chioggia	0.901	0.39**
									Merlin	1.226	0.845**
yield~(ozone_d+sum06)s+co2_d+gdd4+lai	7.33	0.291	6	0.986	441.453	508.711	0.122 ns	0.049	Chioggia	4.178	0.457**
									Merlin	3.152	0.903**
yield~(ozone_d+sum06)+co2_d+gdd4+(solar_d+slrj_d)	21.254	0.095	14	0.96	457.817	536.284	0.186 ns	0.123	Chioggia	10.769	0.387*
									Merlin	10.485	0.848**
yield~ozone_d+co2_d+gdd4+(solar_d+slrj_d)	10.946	0.09	6	0.964	433.93	501.187	0.234 ns	0.116	Chioggia	5.979	0.423**
									Merlin	4.968	0.854**
yield~ozone+co2_d+gdd4+(trcoef+lai)	4.158	0.655	6	1	420.585	487.842	0 ns	0.009	Chioggia	3.484	0.400**
									Merlin	0.674	0.918**
yield~ozone+gdd4+(trcoef+lai)	3.648	0.456	4	1	328.751	379.108	0 ns	0.007	Chioggia	3.345	0.367**
									Merlin	0.303	0.857*
yield~ozone+gdd4+(trcoef+lai)	5.148	0.272	4	0.99	351.509	401.953	0.138 ns	0.092	Chioggia	1.323	0.345**
									Merlin	3.824	0.721*
yield~(ozone+ozone_d)+gdd4+(trcoef+lai)	9.85	0.454	10	1	340.921	402.574	0 ns	0.104	Chioggia	2.869	0.356*
									Merlin	6.981	0.719*
yield~(ozone+ozone_d)+gdd4+slrj_d	3.45	0.485	4	1	329.383	379.826	0 ns	0.019	Chioggia	0.471	0.455**
									Merlin	2.979	0.761**
yield~(ozone+ozone_d)+co2_d+slrj_d	1.283	0.864	4	1	346.723	397.166	0 ns	0.016	Chioggia	0.156	0.416***
									Merlin	1.127	0.876**
yield~(ozone+ozone_d)+co2+slrj_d	1.083	0.897	4	1	348.016	398.459	0 ns	0.019	Chioggia	0.245	0.407***
									Merlin	0.838	0.855*
yield~(ozone+ozone_d)+gdd4+(slrj_d+solarmax_d)	8.903	0.541	10	1	339.902	401.555	0 ns	0.064	Chioggia	4.441	0.395**
									Merlin	4.462	0.738*
yield~(ozone+ozone_d)+gdd4+(slrj_d+solarmax_d)	9.886	0.451	10	1	374.102	435.755	0 ns	0.052	Chioggia	2.309	0.408***
									Merlin	7.577	0.878**
yield~ozone+gdd4+(slrj_d+solarmax_d)	1.884	0.757	4	1	378.46	428.903	0 ns	0.03	Chioggia	0.58	0.393***
									Merlin	1.304	0.875***
yield~(ozone+ozone_d)+gdd4+solarmax_d	**0.686**	**0.953**	**4**	**1**	**347.983**	**398.426**	**0 ns**	**0.015**	**Chioggia**	**0.202**	**0.335*** **
									Merlin	**0.484**	**0.880****

Table 1.10 Beet cultivars structural equation model selection test statistics. Bolded model is the selected model used in the paper. Model parameters outside of parenthesis are manifest variable and parameters inside of a parenthesis represent a latent variable. Model parameters are defined as followed; *vpd_d* is the daytime vapor pressure deficite average, *solar_d* and *solarmax_d* are the daytime average light radiance and daytime hourly maximal light radiance, *slrj_d* is the daytime radiant exposure, *dist_cc* and *gps_w* are the distance to the city center and the gps west coordinate of each garden respectively, *temp_d* and *temp_n* are the average temperature in the daytime and nighttime respectively, and *trcoef* and *lai* are the canopy transmission coefficient and canopy light area index respectively. All other model parameters are defined in the text. Model χ^2 is the model test of the baseline model, k is degrees of freedom of the model, AIC and BIC are Akaike weights and Bayesian weights, respectively. CFI is comparative fit index scaled from 0-1 with 1 being the best fit. RMSEA is the root mean square error of approximation on a scale from 0-1 with 0 being the best fit. SRMR is standardized root mean square residual on a scale of 0-1 with 0 being the best fit. Variety χ^2 is the proportion of the model χ^2 taken up by each variety. R^2 is the total variation within variety accounted for by the model. ns represents non-significance, * is significance at the 0.05 level, ** is significance at the 0.01 level, and *** is significance at the 0.001 level.

Model	Test Stat	Model χ^2	k	CFI	AIC	BIC	RMSEA	SRMR	Variety	Variety χ^2	R^2
biomass~ozone_d+co2_d+(temp_d+temp_n)+(slrj_d+solar_d)	35.604	0.001	14	0.919	407.362	485.829	0.321**	0.103	Diablo	18.66	0.556**
									Long Island	16.944	0.969**
biomass~aot40+co2_d+(temp_d+temp_n)+slrj_d	12.047	0.047	6	0.961	396.586	463.843	0.274*	0.015	Diablo	8.202	0.535***
									Long Island	4.571	0.974*
biomass~co2_d+(temp_d+temp_n)+slrj_d	7.592	0.108	4	0.977	314.697	365.141	0.245 ns	0.017	Diablo	3.867	0.525***
									Long Island	3.725	0.973 ns
biomass~co2_d+(temp_d+temp_n)+aot40	1.899	0.754	4	1	325.377	375.377	0 ns	0.017	Diablo	1.253	0.427**
									Long Island	0.646	0.976 ns
biomass~co2_d+(temp_d+temp_n)+ozone_d	3.892	0.421	4	1	323.632	374.075	0 ns	0.02	Diablo	1.156	0.467**
									Long Island	2.736	0.976 ns
biomass~co2_d+(temp_d+temp_n)+(trcoef+lai)	13.332	0.206	10	0.985	344.662	406.315	0.149 ns	0.038	Diablo	6.952	0.427**
									Long Island	6.38	0.975*
biomass~co2_d+gdd4+(trcoef+lai)	0.682	0.952	4	1	368.247	418.69	0 ns	0.026	Diablo	0.362	0.010*
									Long Island	0.329	0.810**
biomass~co2_d+gdd4+(trcoef+lai)	0.803	0.938	4	1	332.975	383.418	0 ns	0.033	Diablo	0.486	0.456**
									Long Island	0.317	0.968**
biomass~co2_d+(temp_d+temp_n)+solar_d	5.066	0.281	4	0.922	332.326	382.769	0.133 ns	0.016	Diablo	2.802	0.481***
									Long Island	2.264	0.978*
biomass~co2_d+(temp_d+temp_n)+ozone_d+trcoef	14.52	0.024	6	0.952	389.851	457.108	0.308*	0.026	Diablo	8.352	0.640**
									Long Island	6.169	0.979 ns
biomass~co2_d+(temp_d+temp_n)+ozone_d+solar_d	15.844	0.015	6	0.939	406.652	473.909	0.331*	0.033	Diablo	5.87	0.553*
									Long Island	9.975	0.979 ns
biomass~co2_d+(temp_d+temp_n)+ozone_d+lai	12.887	0.045	6	0.961	390.318	457.575	0.277 ns	0.023	Diablo	7.742	0.612**
									Long Island	5.145	0.982 ns
biomass~(temp_d+temp_n)+ozone_d+lai	6.289	0.179	4	0.985	312.132	362.575	0.195 ns	0.042	Diablo	3.713	0.478 ns
									Long Island	2.577	0.832 ns
biomass~(temp_d+temp_n)+ozone_d+dist_cc	9.355	0.053	4	0.959	333.935	384.378	0.299 ns	0.05	Diablo	3.917	0.2*
									Long Island	5.438	0.85*
biomass~(temp_d+temp_n)+ozone_d+slrj_d	13.639	0.009	4	0.936	315.857	366.3	0.401*	0.046	Diablo	7.601	0.533*
									Long Island	6.039	0.742**
biomass~(temp_d+temp_n)+sum06+co2_d	2.121	0.714	4	1	320.139	370.582	0 ns	0.019	Diablo	1.483	0.407**
									Long Island	0.638	0.973 ns
biomass~(temp_d+temp_n)+aot40+co2	1.036	0.904	4	1	326.43	376.873	0 ns	0.007	Diablo	0.962	0.492**
									Long Island	0.074	0.963*
biomass~(temp_d+temp)+aot40+co2	1.032	0.905	4	1	278.846	329.289	0 ns	0.007	Diablo	0.96	0.474**
									Long Island	0.072	0.962**
biomass~(temp_n+temp)+aot40+co2	1.039	0.904	4	1	291.043	341.486	0 ns	0.005	Diablo	0.963	0.491**
									Long Island	0.076	0.944**
biomass~(temp_n+temp)+co2	**0.245**	**0.885**	**2**	**1**	**207.75**	**244.181**	**0 ns**	**0.004**	**Diablo**	**0.19**	**0.498****
									Long Island	**0.056**	**0.941****
biomass~co2+(temp+temp_n)+(trcoef+lai)	10.576	0.391	10	0.998	308.861	370.513	0.062 ns	0.041	Diablo	5.789	0.502**
									Long Island	4.788	0.928***
biomass~co2+(temp+temp_n)+lai	7.886	0.096	4	0.976	307.11	357.554	0.254 ns	0.022	Diablo	4.517	0.494**
									Long Island	3.369	0.932***
biomass~co2+(temp+temp_n)+solar_d	2.61	0.625	4	1	296.284	346.727	0 ns	0.013	Diablo	1.316	0.501***
									Long Island	1.298	0.948***
biomass~co2+temp+(solar_d+solar)	7.613	0.107	4	0.989	146.976	197.419	0.245 ns	0.122	Diablo	3.228	0.528**
									Long Island	4.385	0.953**
biomass~co2+temp+lai	1.123	0.891	4	1	358.874	409.317	0 ns	0.044	Diablo	0.136	0.498**
									Long Island	0.987	0.952**

Table 1.11 Brussels sprouts cultivars structural equation model selection test statistics. Bolded model is the selected model used in the paper. Model parameters outside of parenthesis are manifest variable and parameters inside of a parenthesis represent a latent variable. Model parameters are defined as followed; *vpd_d* is the daytime vapor pressure deficite average, *solar_d* and *solarmax_d* are the daytime average light radiance and daytime hourly maximal light radiance, *slrj_d* is the daytime radiant exposure, *dist_cc* and *gps_w* are the distance to the city center and the gps west coordinate of each garden respectively, *temp_d* and *temp_n* are the average temperature in the daytime and nighttime respectively, and *trcoef* and *lai* are the canopy transmission coefficient and canopy light area index respectively. All other model parameters are defined in the text. Model χ^2 is the model test of the baseline model, k is degrees of freedom of the model, AIC and BIC are Akaike weights and Bayesian weights, respectively. CFI is comparative fit index scaled from 0-1 with 1 being the best fit. RMSEA is the root mean square error of approximation on a scale from 0-1 with 0 being the best fit. SRMR is standardized root mean square residual on a scale of 0-1 with 0 being the best fit. Variety χ^2 is the proportion of the model χ^2 taken up by each variety. R^2 is the total variation within variety accounted for by the model. ns represents non-significance, * is significance at the 0.05 level, ** is significance at the 0.01 level, and *** is significance at the 0.001 level.

Figures

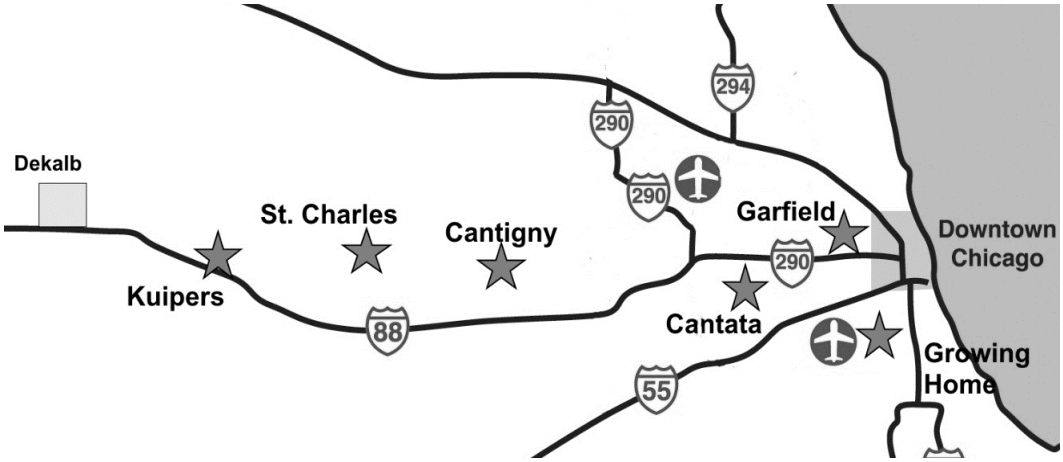

Fig. 1.1 Map of experimental garden sites across the Chicago, IL metro region. Sites are indicated by stars and adjacent labels. 'Rural' sites included Kuipers and St. Charles, 'peri-urban' sites include Cantigny and Cantata, and 'urban' sites included Garfield and Growing Home.

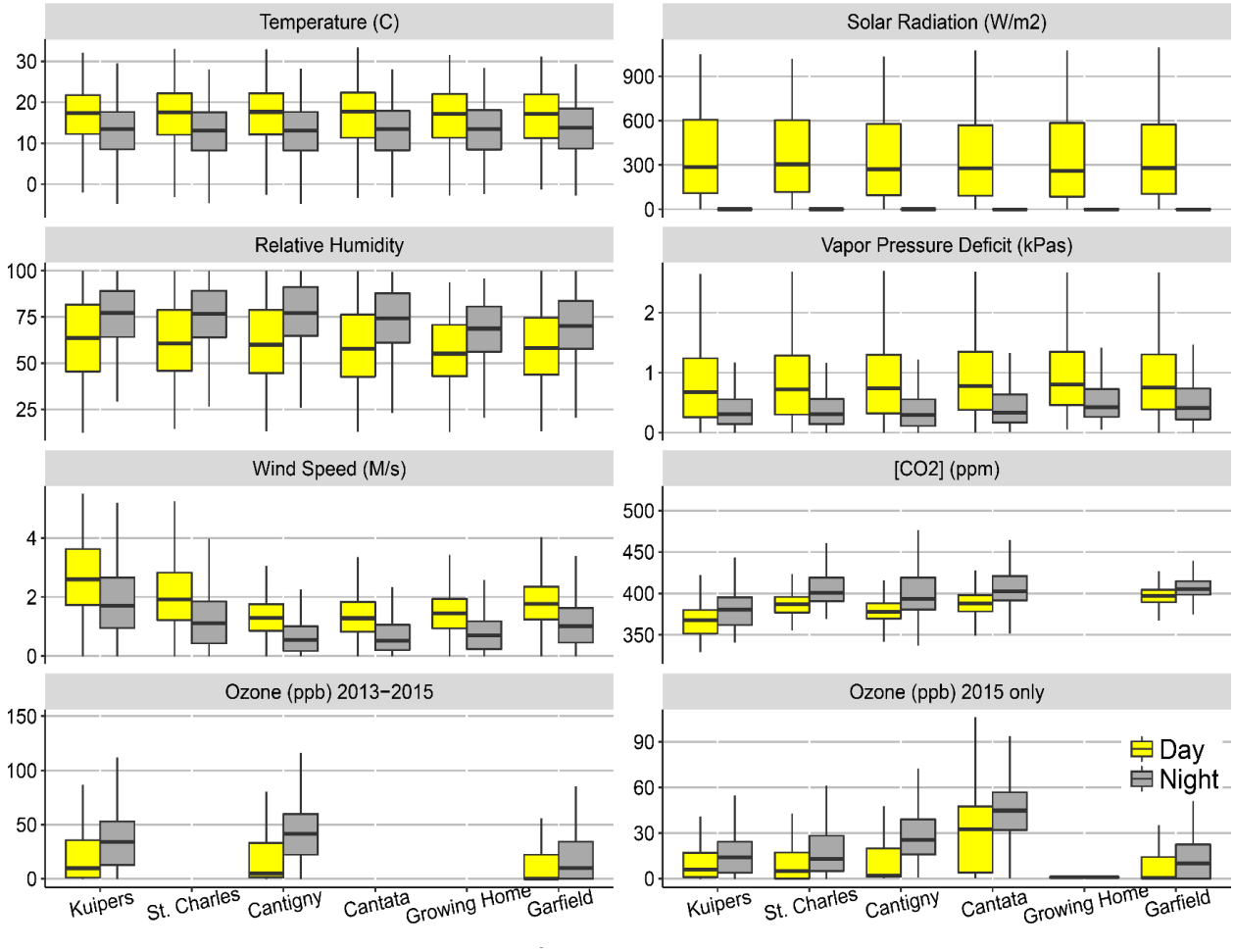

Fig. 1.2 Boxplots for spring micrometeorological measures from towers adjacent to the research sites. These panels are hourly averages from April 8th to June 15th averaged across 2013, 2014, and 2015. Research sites are arranged on the horizontal axis by proximity to city center from left (rural) to right (urban). Units of each vertical axis are included above each plot in parentheses. Yellow boxes represent daytime hours from 0530 to 1930 and grey boxes are nighttime hours. Three ozone monitors were installed in 2013 and 2014 and all six sites had ozone monitors in 2015. A CO_2 IRGA was not installed at the urban Growing Home site.

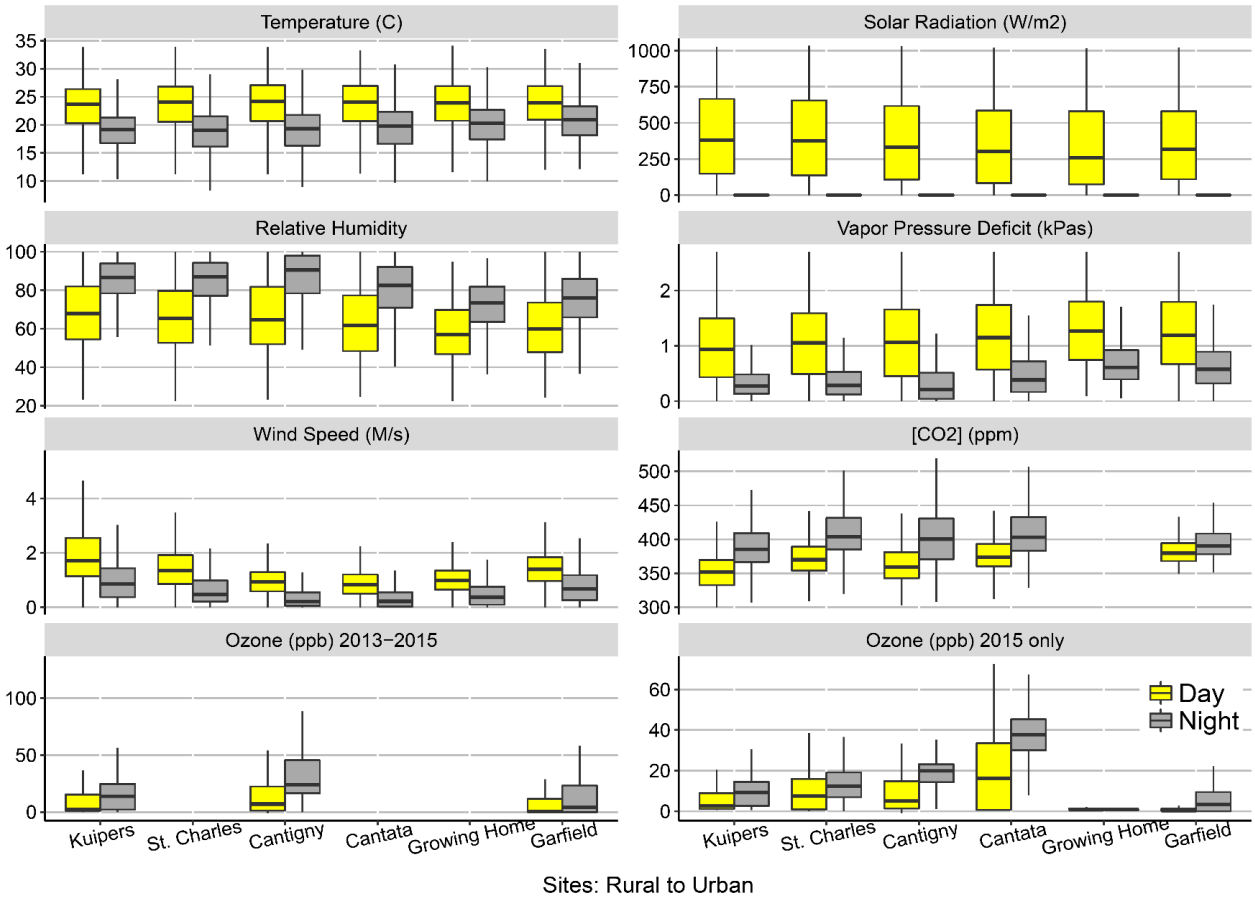

Fig. 1.3 Boxplots for summer micrometeorological measures from towers adjacent to the research sites. These panels are hourly averages from June 15th to September 1st of a culmination of 2013, 2014, and 2015. Research sites are arranged on the horizontal axis by proximity to city center from left (rural) to right (urban). Units of each vertical axis are included above each plot in parentheses. Yellow boxes represent daytime hours from 0530 to 1930 and grey boxes are nighttime hours. Three ozone monitors were installed in 2013 and 2014 and all six sites had ozone monitors in 2015. A CO_2 IRGA was not installed at the urban Growing Home site.

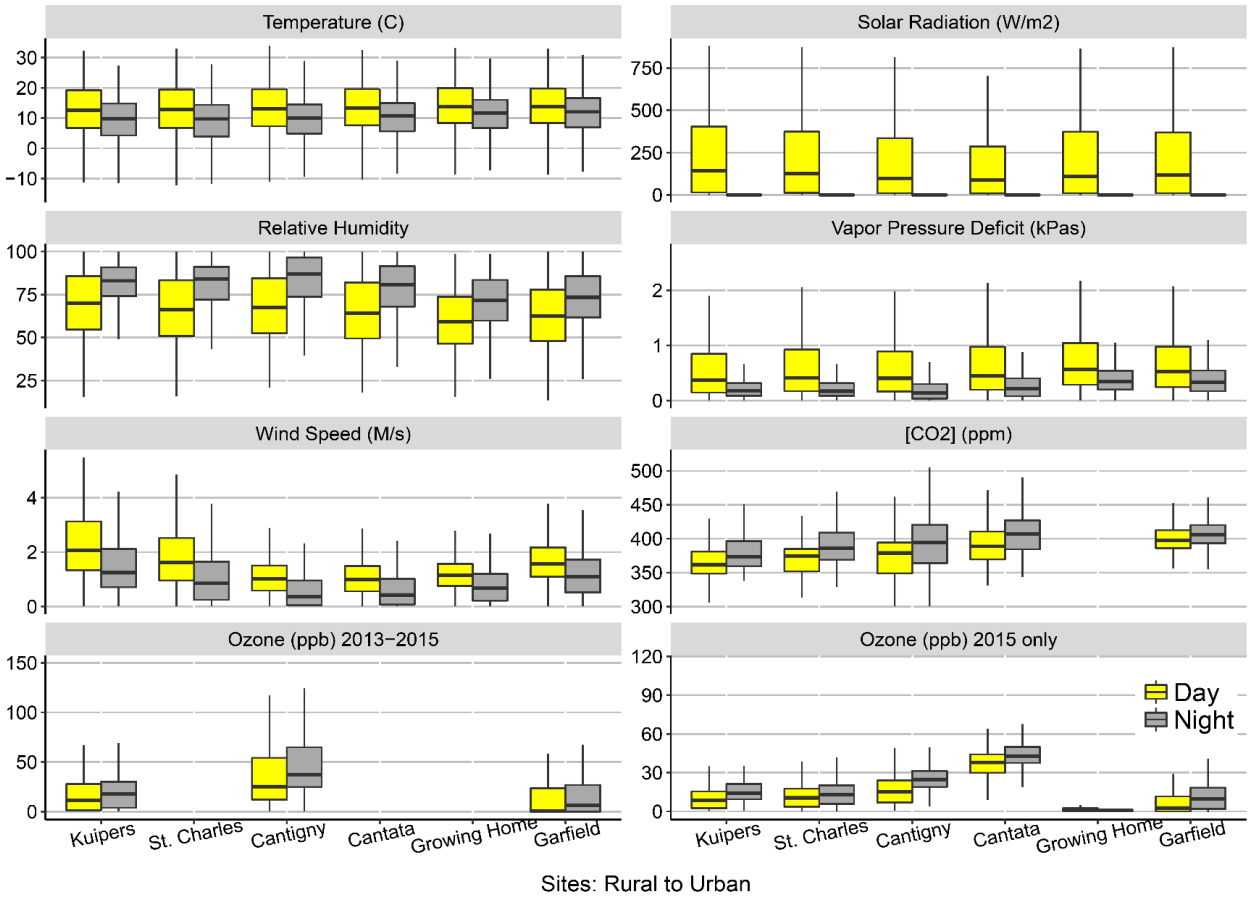

Fig. 1.4 Boxplots for fall micrometeorological measures from towers adjacent to the research sites. These panels are hourly averages from September 1st to December 1st of a culmination of 2013, 2014, and 2015. Research sites are arranged on the horizontal axis by proximity to city center from left (rural) to right (urban). Units of each vertical axis are included above each plot in parentheses. Yellow boxes represent daytime hours from 0530 to 1930 and grey boxes are nighttime hours. Three ozone monitors were installed in 2013 and 2014 and all six sites had ozone monitors in 2015. A CO_2 IRGA was not installed at the urban Growing Home site.

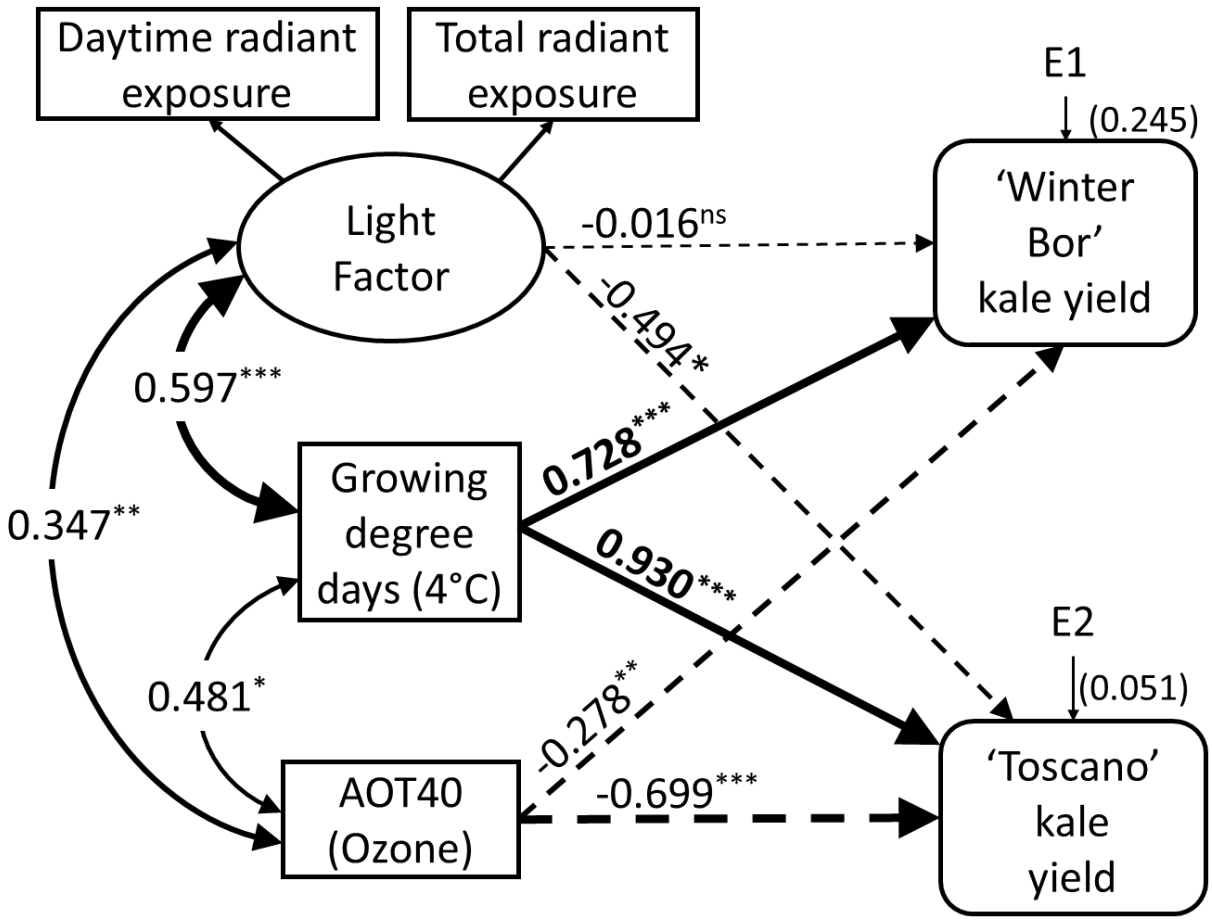

Fig. 1.5 Structural equation pathway model for two cultivars of spring-planted kale. Hybrid variety ('Winter Bor') is on top and heirloom variety ('Toscano') is on bottom. Response variables are presented by boxes with rounded corners. Predictor variables include latent variables in ovals and manifest variables in rectangles. Solid straight arrows denote positive and dotted lines denote negative causal pathways (where * and *** represent $P < 0.05$ and $P < 0.001$), with standardized regression coefficients indicating relationship strength. Double-headed arrows represent correlations among latent and manifest predictor variables. E1 and E2 are unexplained variation in the model.

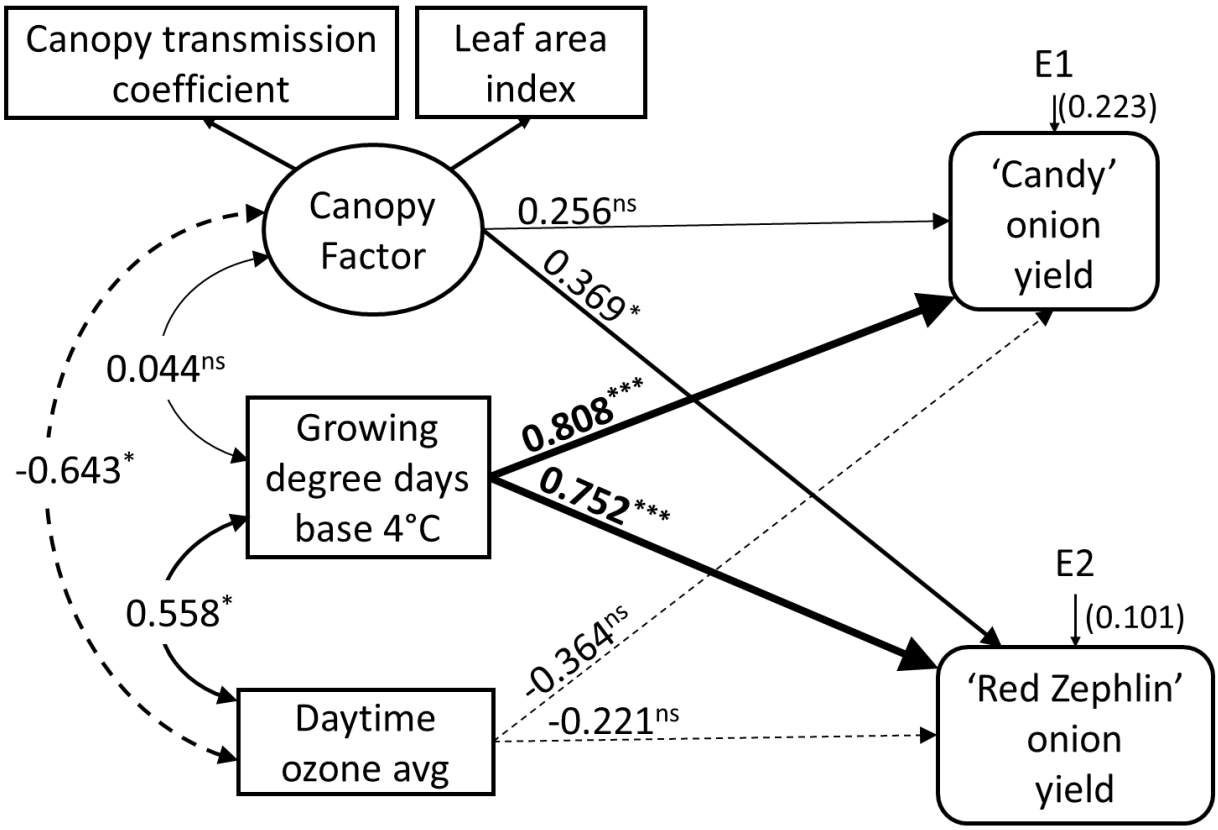

Fig. 1.6 Structural equation pathway model for two cultivars of spring-planted onions. Response variable is average individual onion weight. Both cultivars are hybrid. Response variables are presented by boxes with rounded corners. Predictor variables include latent variables in ovals and manifest variables in rectangles. Solid arrows denote positive and dotted lines denote negative causal pathways (where * and *** represent $P < 0.05$ and $P < 0.001$), with standardized regression coefficients indicating relationship strength. Double-headed arrows represent correlations among latent and manifest predictor variables. E1 and E2 are unexplained variation in the model.

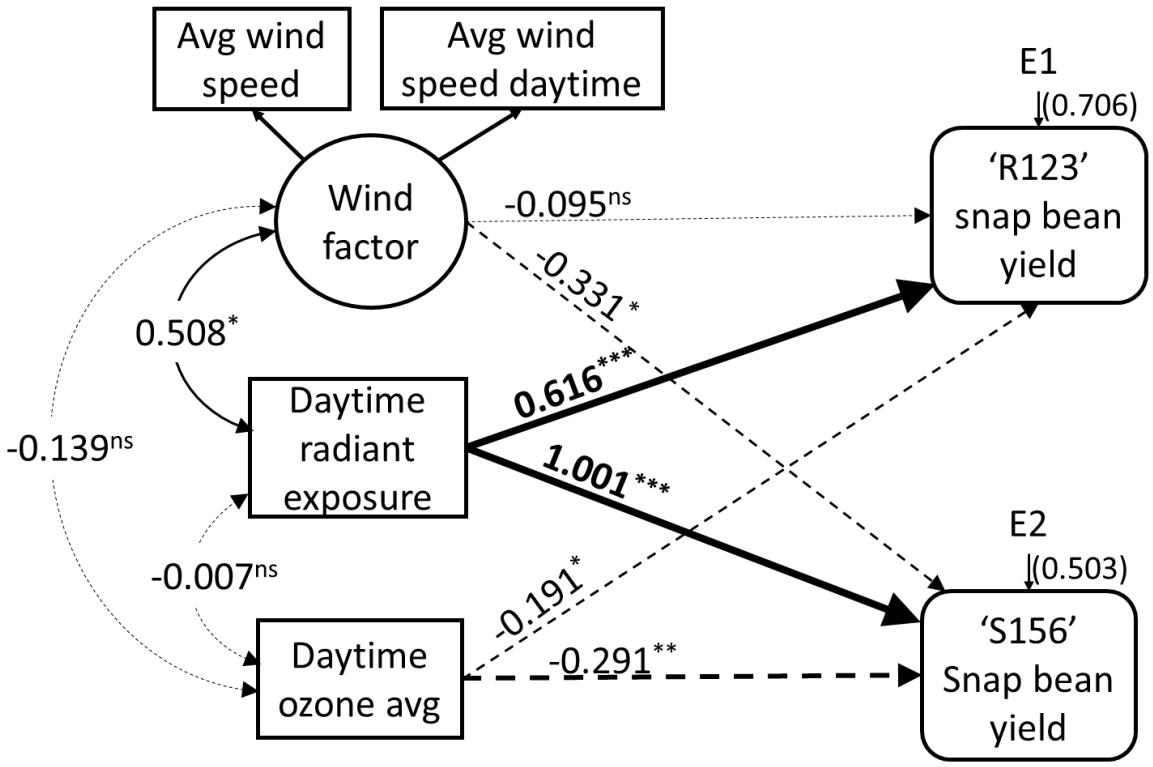

Fig. 1.7 Structural equation pathway model for summer-planted bean ozone resistant (R123) and ozone susceptible (S156) cultivars. Response variables are presented by boxes with rounded corners. Predictor variables include latent variables in ovals and manifest variables in rectangles. Solid straight arrows denote positive and dotted lines denote negative causal pathways (where * and *** represent $P < 0.05$ and $P < 0.001$), with standardized regression coefficients indicating relationship strength. Double-headed arrows represent correlations among latent and manifest predictor variables. E1 and E2 are unexplained variation in the model.

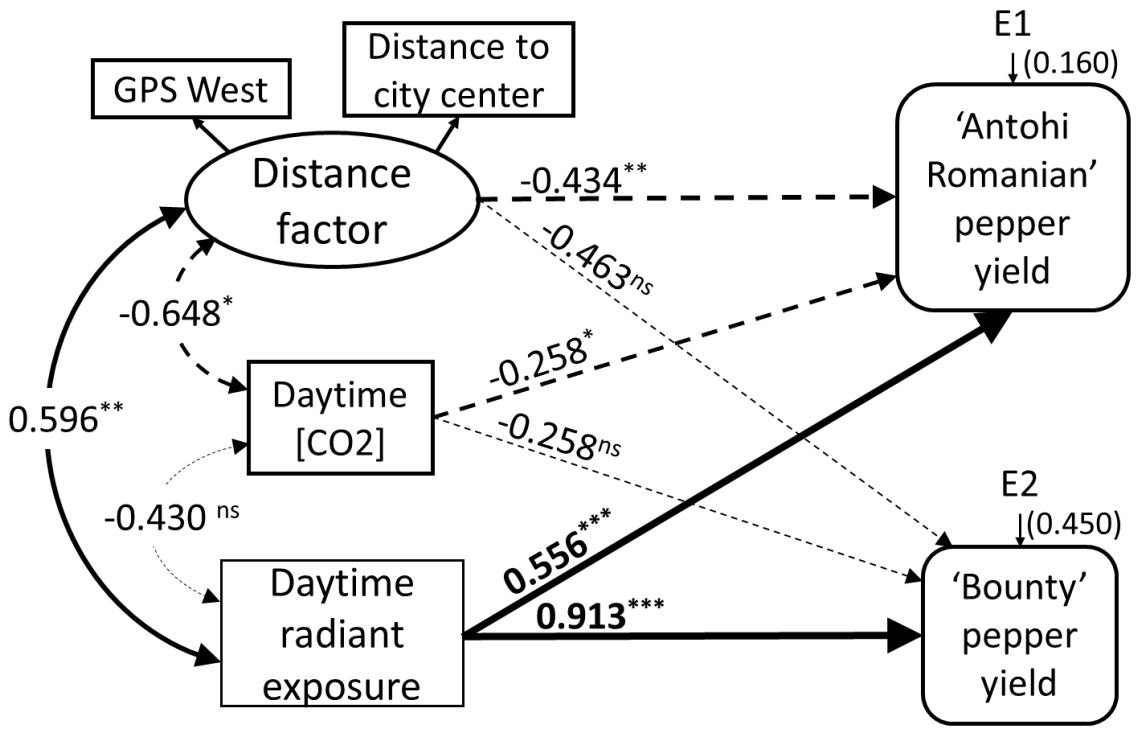

Fig. 1.8 Structural equation pathway model for summer planted peppers. Varieties include heirloom 'Anthohi Romanian' and hybrid 'Bounty'. Response variables are presented by boxes with rounded corners. Predictor variables include latent variables in ovals and manifest variables in rectangles. Solid straight arrows denote positive and dotted lines denote negative causal pathways (where * and *** represent $P < 0.05$ and $P < 0.001$), with standardized regression coefficients indicating relationship strength. Double-headed arrows represent correlations among latent and manifest predictor variables. E1 and E2 are unexplained variation in the model.

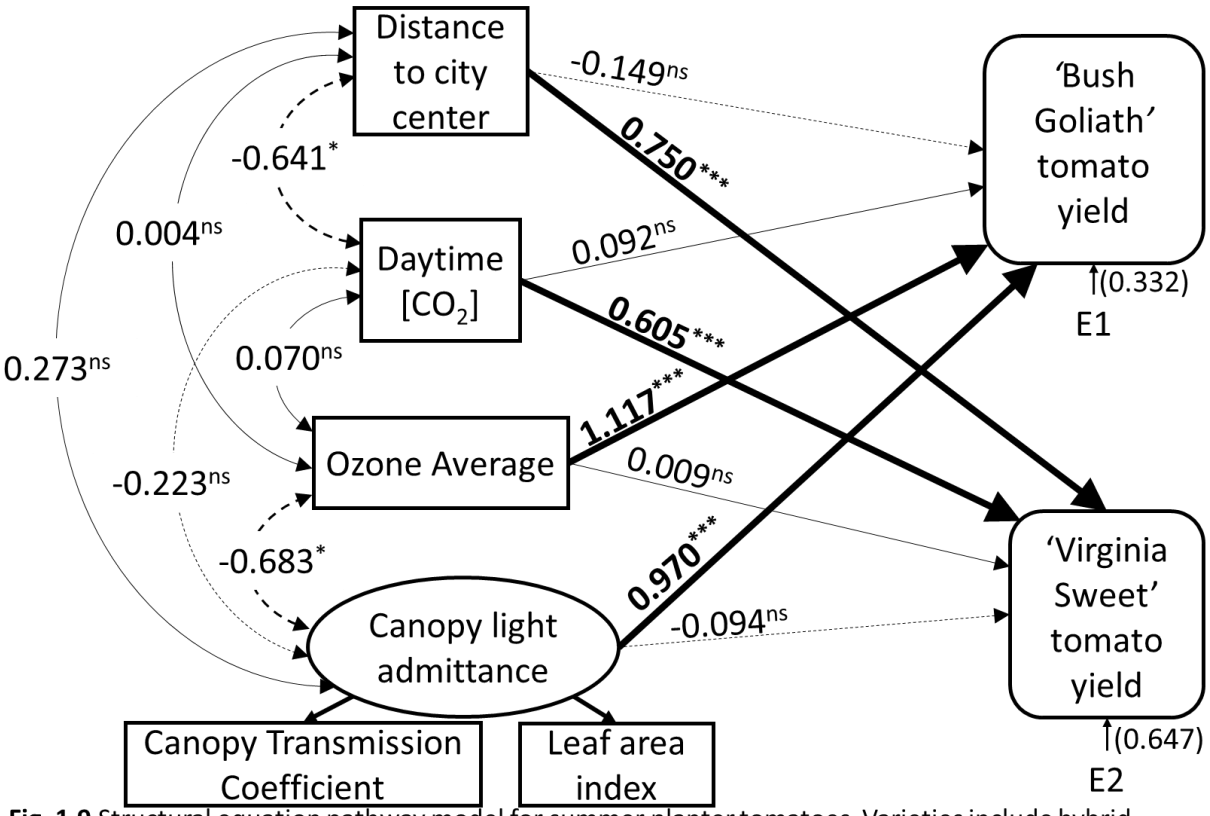

Fig. 1.9 Structural equation pathway model for summer planter tomatoes. Varieties include hybrid 'Bush Goliath' and heirloom 'Virginia Sweet'. Response variables are presented by boxes with rounded corners. Predictor variables include latent variables in ovals and manifest variables in rectangles. Solid straight arrows denote positive and dotted lines denote negative causal pathways (where * and *** represent $P < 0.05$ and $P < 0.001$), with standardized regression coefficients indicating relationship strength. Double-headed arrows represent correlations among latent and manifest predictor variables. E1 and E2 are unexplained variation in the model.

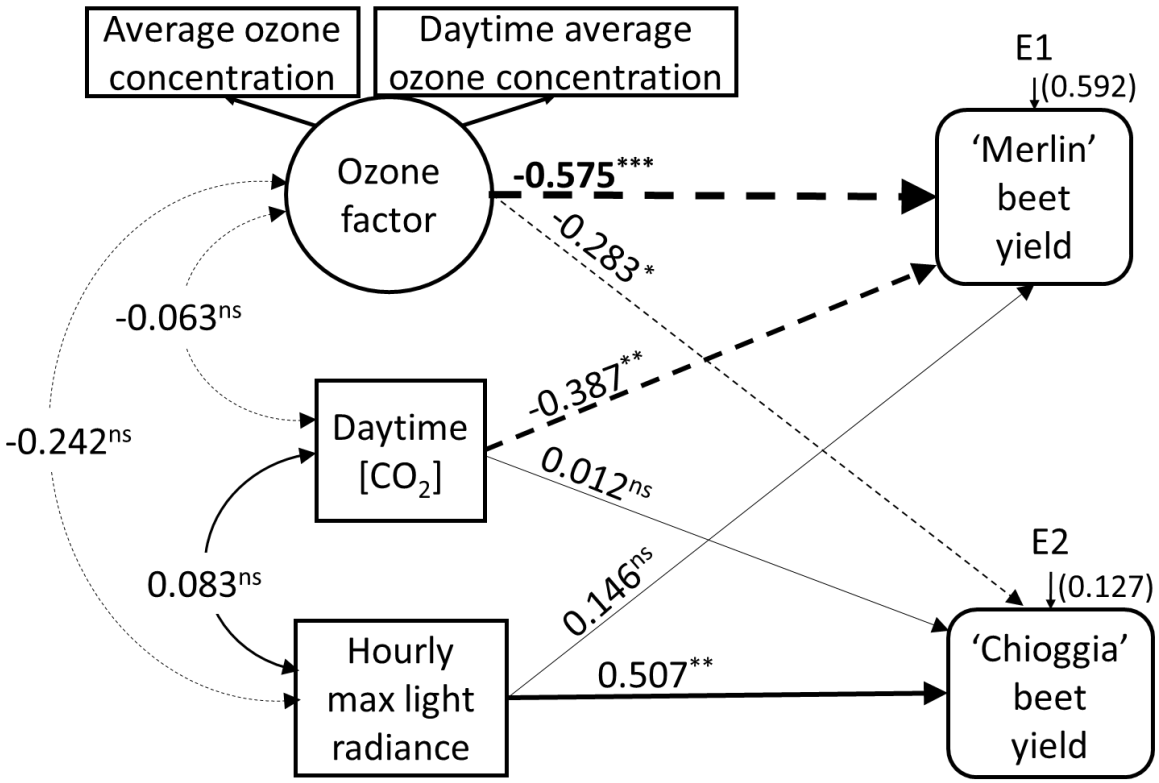

Fig. 1.10 Structural equation pathway model for fall planted beets. Varieties include hybrid 'Merlin' and heirloom 'Chioggia'. Response variables are presented by boxes with rounded corners. Predictor variables include latent variables in ovals and manifest variables in rectangles. Solid straight arrows denote positive and dotted lines denote negative causal pathways (where * and *** represent $P < 0.05$ and $P < 0.001$), with standardized regression coefficients indicating relationship strength. Double-headed arrows represent correlations among latent and manifest predictor variables. E1 and E2 are unexplained variation in the model.

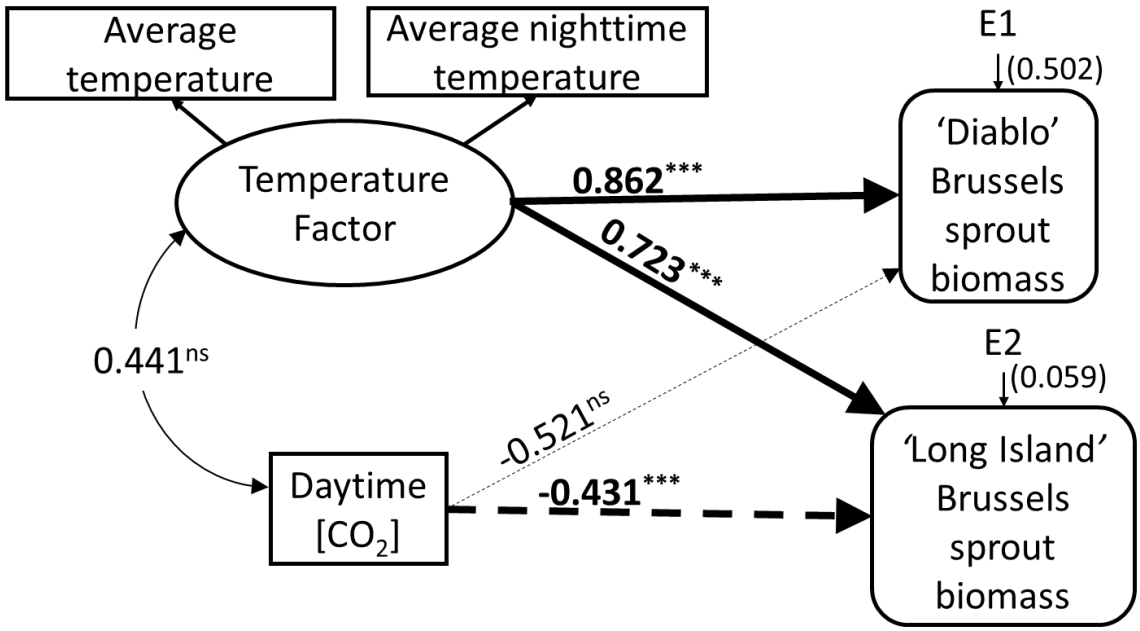

Fig 1.11 Structural equation pathway model for fall planted Brussels sprouts total biomass compared to micrometeorological measures. Varieties include hybrid 'Diablo' and heirloom 'Long Island'. Response variables are presented by boxes with rounded corners. Predictor variables include latent variables in ovals and manifest variables in rectangles. Solid straight arrows denote positive and dotted lines denote negative causal pathways (where * and *** represent $P < 0.05$ and $P < 0.001$), with standardized regression coefficients indicating relationship strength. Double-headed arrows represent correlations among latent and manifest predictor variables. E1 and E2 are unexplained variation in the model.

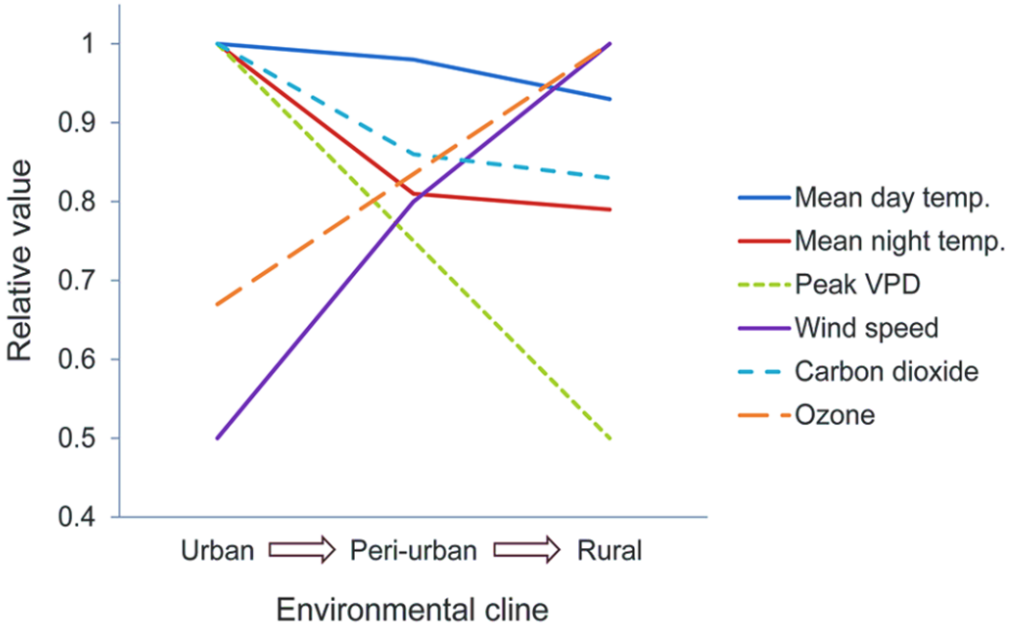

Fig. 1.12 Hypothesized changes in relative values for microclimatic factors and atmospheric pollutants along an urban to rural environmental cline. Taken from Wortman and Lovell (2013).

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CHAPTER 2: EFFECTS OF THE URBAN ENVIRONMENT ON SOIL CHEMICAL AND MICROBIAL PROPERTIES IN A RAISED BED VEGETABLE PRODUCTION SYSTEM

Abstract

Heavy metal contamination is prevalent in urban areas and presents a challenge for urban food production and gardening. Capping soil with clean media or raised-beds is an advantageous strategy that eliminates contact with contaminated soils, but previous research has demonstrated the possibility of heavy-metal aerial recontamination. Compost-based raised-bed soil heavy metal recontamination, nutrient dynamics, and soil microbial dynamics were assessed in six gardens along an urban to rural transect in Chicago. Individual garden beds were composed of 50% yard waste compost, 40% topsoil, and 10% sand. Seven common species of vegetables were grown in beds from 2013 to 2015. Soil samples for chemical assessment of agriculture soils were taken in spring 2013 and 2015. Lead content from possible deposition was assessed by Mehlich-3 extraction in fall 2013 and 2014 and spring 2014 and 2015 and EPA method 200.5 in fall 2015. Plant root simulator (PRS) probes were used in July 2014, May 2015, and September 2016 to determine nutrients and metals available in soil solution. Phospho-lipid fatty acid (PLFA) biomarkers, sampled in fall 2014 and 2015 and spring 2015, were used to assess soil microbial dynamics. Lead levels did not increase significantly in any garden over the three years. Initial soil samples had high salt levels, but 2015 samples suggest that a large portion of the salts had leached out of the surface profile of the beds. Soil organic matter content increased from 13.5 to 15% between 2013 and 2015 and phosphorus levels increased two-fold. Nitrogen levels in solution increased two-fold from 2014 to 2015 samplings. PLFA markers showed low bacteria:fungi ratios and low saturated:unsaturated ratios indicating soils with low stress.

Temperature was positively correlated with several PLFA biomarkers and ozone levels were negatively associated. Sampling date had the largest effect on PLFA levels, not microclimate or plant productivity. Very few differences were found among six gardens across the urban to rural gradient for PLFA markers, soil lead levels, or available nutrients. Results indicate that compost based raised-bed systems in Chicago, IL are safe from short-term heavy metal recontamination and are a viable production system for urban food production.

Introduction

Urban Soil Contamination

Urban agriculture is a growing trend and production occurs at various scales including market farms, community and school gardens, and home gardens (Mok et al., 2007). This increase includes members from many socioeconomic and ethnic backgrounds (Wakefield et al., 2007; Taylor and Lovell, 2012). Urban agriculture provides benefits to health, wellbeing, and sense of community (Alaimo et al., 2008). Unfortunately, urban soils can be compacted, low in fertility and organic matter, and are often polluted with waste materials (e.g., glass, plastic, and bricks) and lead-based paint chips (Beniston and Lal, 2012). Urban soils are also more likely to be contaminated with toxins including polycyclic aromatic hydrocarbons (Srogi, 2007) and heavy metals such as lead, chromium, cadmium, zinc, arsenic, and copper (Charlesworth et al., 2010), with lead being the most prevalent and potentially harmful to humans.

Human lead exposure is neurodegenerative and particularly effects children. Canfield et al. (2003) found that there was a negative linear association between blood serum lead level and parental adjusted IQ scores of 172 children from 3-5 years old up to 20 µL/dL (200 ppm). Urban lead exposure disproportionately impacts racial minorities and impoverished communities (Filippelli and Laidlaw, 2010) and it is the children in these communities who are most likely to

experience negative health effects (Mielke et al., 1983, 1999). Recently proposed EPA regulation changes lowering the acceptable blood serum lead levels to 5µL/dL from 10 µL/dL (CDC, 2015) will increase the need to mitigate urban soil contamination exposure (Henry et al., 2015).

Lead is naturally occurring at non-toxic levels in soil, but contamination from industrial activities, leaded paint, and leaded vehicle exhaust makes lead more prevalent in every city (Charlesworth et al., 2010). Lead levels above 400 mg kg^{-1}, according to the EPA, are potentially hazardous and food crops should not be grown in the soils with this level of contamination (USEPA, 2011). This standard is exceeded in residential soils in 30% of 61 sites in Baltimore, MD (Schwarz et al., 2012). In Chicago, IL 57 random sites had average soil lead levels of 395 mg kg^{-1} (Kay et al., 2008). Soil samples from 5467 soil samples from New Orleans had a median lead concentration of 1051 mg kg^{-1} (Mielke et al., 2006).

Exposure to lead in cities happens through direct ingestion of contaminated soils, dust particles of contaminated soil, and water sources (Filippelli and Laidlaw, 2010). Soil ingestion of dust and soil was found to account for 72-91% of lead exposure in children in Boston, MA, produce ingestion accounted for 2-3%, and 1-5% was from water sources (Clark et al., 2008). Most food crops do not accumulate dangerous amounts of lead from contaminated soils, although edible leaves and roots tend to accumulate higher levels than fruits (Finster et al., 2004). McBride et al. (2015) suggest that in soils with over 200 mg kg^{-1} lead concentrations, leafy vegetables and root crops should not be grown. There is little effect of soil lead on plant growth unless concentrations are extremely elevated (Zaman and Zereen, 1998). Aerial suspension of contaminants happens most readily next to busy roads and adjacent to vacant lots in neighborhoods with aging housing stock (Laidlaw et al., 2012). Lead aerial redeposition reportedly increased soil lead levels in 25 raised bed gardens an average of 24 mg kg^{-1} yr^{-1} in

Boston, MA (Clark et al., 2008). Historically, leaded gasoline was the primary source of most aerially deposited lead (Mielke and Reagan, 1998), but because leaded gasoline use has been discontinued, bare soil is now the major source and the contaminant is moved by wind, water runoff, and disturbance activities (Hosiokangas et al., 2004). When contaminated soil particles are deposited on or near roadways, they are resuspended by traffic or wind, which makes areas near roadways most susceptible to heavy metal deposition (Nabulo et al., 2006; Zereini et al., 2007).

Soil Reclamation

There are several means of remediating heavy metal contaminated urban soils including; 1) soil evacuation and back filling with uncontaminated soil and/or compost, 2) capping contaminated soil with impermeable (e.g., cement or clay) or permeable layers (e.g., woodchips or gravel) and back filling with uncontaminated soil and/or compost, 3) phytoremediation and phytostabilization of contaminants *in situ*, 4) and chemically stabilizing contaminants in the soil to limit plant uptake and bioavailability. The implementation of remediation involves understanding the level of contamination through sampling, then making a decision based upon laws, cost, and future use of the site (Burns et al., 1996). Evacuation of soil is expensive and technically complicated and is not feasible for many urban applications (Cheng, 2009; Thornton, 1991). Although there is interest in phytoremediation and phytostabilization, there have not been systems proven effective enough or cost effective for wide spread use (Chaney et al., 2010). Capping strategies have been more widely adopted for restoration of urban public and food production areas (Mielke et al., 2006; Filippelli and Laidlaw, 2010). One novel approach was demonstrated by Mielke et al. (2006), who used dredged river alluvium in New Orleans to cap contaminated soil, which was cost-effective and reduced surface lead concentrations below 20

mg kg^{-1} (Mielke et al., 2006). The cost of capping depends on whether the soil needs to be isolated with impermeable barriers and the quality of the capping material (Henry et al., 2015), although the site is available immediately for repurpose. Soil stabilization (*in situ* remediation) of contaminants is the stabilization of nutrients in the soil. This method uses soil additions to adjust the pH (by lime or sulfur application) to cause the formation of more stable compounds or the addition of organic material to dilute and stabilize the contaminant (Henry et al., 2015). Another method is adding phosphorus fertilizer to form more stable and less bioavailable polymorphites (Hettiarachchi et al., 2000). *In situ r*emediation does not eliminate the possibility of human exposure, but is the least expensive of the remediation strategies (Hettiarachchi and Pierzynski, 2004).

For food production, a raised bed garden with an impermeable soil cap is a simple way to exclude contaminated soils from the growing media. However, because the largest threat of human contact with contaminants is direct soil consumption, some type of cap (e.g., woodchips) or vegetation should be used to prevent human contact with soils around the raised beds (Henry et al., 2015). Because of particulate redeposition, raised beds and cap-and-fill garden proximity to contaminated soils and roadways determine, in large part, the potential for heavy metal contamination (Laidlaw et al., 2012). Because most raised-bed and cap systems use fill material consisting of high organic material, any future contaminants may be stabilized by pH buffering and organic matter diluting and binding the contaminant.

Urban Raised-bed Soil Ecology

In the urban environment, there exists a cline of microclimatic conditions from the built city center to adjacent natural or agricultural dominated lands (Medley et al., 1995). Urban centers have higher temperatures, lower humidity, and increased aerial pollutants (Molina and

Molina, 2004; Wortman and Lovell, 2013). Kaye et al. (2005) found that higher temperature, soil available C and N, and supplemental irrigation lead to a two fold increase in microbial biomass and higher C and N turnover in urban soils compared to rural in Denver, CO. Byrne (2007) outlines the effects of urbanization on soil ecology, microbial dynamics, and nutrients in various urban soils. Overall, the management and vegetative cover of the soil typically has a greater impact on soil physical and microbial properties than microclimate or proximity to the city (Byrne, 2007). Although, higher temperatures and soil moisture deficit may cause significant changes in soil ecological function within highly built environments (Byrne, 2007). Reese et al. (2016) found that soil microbial populations and diversity were largely unaffected by location or patch size in Manhattan, NYC.

In a study of green roof soil fungal biodiversity in New York City, McGuire et al. (2013) found that fungal diversity and biomass were dependent on soil type and water status, but not distance to city center or temperature. As temperature rises and frost-free days increase in cities, soil microbial populations and nutrient turnover rates will likely increase, possibly tying nutrients up in microbial biomass (Bossio et al., 1998). Nutrient leaching in newly composted material could be a potential issue in raised bed or capped soils (Hargreaves et al., 2008). The effects of urbanization on high organic material growing media, which is used on countless urban gardens and farms, has not been studied directly.

Objectives

Lead recontamination, soil nutrients and plant available heavy metals, and soil microbial dynamics were measured across six raised bed gardens and three years to quantify compost-based soil dynamics across an urban to rural gradient in greater Chicago, IL.

Materials and Methods

Six experimental gardens (sites) in the Chicago, IL area were established in spring 2013. Gardens were located along a latitudinal corridor close to 41° 50' N ranging from near the city center to rural agricultural areas (Fig. 2.1). Each garden contained forty 0.43 m^3 containers (Smartpot™, High Caliper Growing Systems, Oklahoma City, OK) filled with 50% leaf litter compost, 40% topsoil, and 10% sand/vermiculite mix (60% sand, 20% silt, and 20% clay by textural analysis). Soil was prepared from the same commercial batch (Lake Street Landscape Supply, Inc.; Chicago IL), and trucked to each garden. Each pot was refilled with approximately 0.07 m^3 (about 15% total volume) of the same soil mix in spring 2014 because of soil settling in 2013. Raised beds were planted in the spring with kale (*Brassica oleracea L.*) and onion (*Allium cepa L.*), in the summer with tomato (*Solanum lycopersicum L.*), pepper (*Capsicum annuum L.*), and snap bean (*Phaseolus vulgaris L.*), and following spring crops in the fall with crop species table beet (*Beta vulgaris subsp. vulgaris*) and Brussels sprouts (*Brassica oleracea L.* var. gemmifera). Soil was maintained near field capacity with drip irrigation measured with moisture sensors (200SS Watermark sensors, Irrometer Inc, Riverside, CA). Soil temperature was continually monitored (HOBO Pendant Loggers; Onset Computer Corp., Bourne, MA) at a depth of 5 cm in a random selection of ten of the forty pots in each garden.

Weather towers were located directly adjacent to each experimental garden and equipped with micrometeorological and trace gas sensors, and data loggers (CR10X, Campbell Scientific, Logan, UT). Sensors included a HMP45 temperature and relative humidity probe (Campbell Scientific, Logan, UT), cup anemometer and wind vein (Davis Instruments Corp, Hayward, CA), SP-110 pyranometer (Apogee Instruments Inc., Logan, UT), SBA-5 CO_2 infrared gas analyzer

(IRGA) (PP Systems Inc., Amesbury, MA), and an F-12 toxic gas analyzer with 0-1000 parts per billion (ppb) ozone sensor (Analytical Technology, Inc., Collegeville, PA).

Prior to planting crops in 2013, a 1000 g soil sample was taken (a composite of twenty subsamples) from soils delivered to each garden and sent to Brookside Laboratories (New Bremen, OH) for extraction and analysis of essential plant nutrients and chemical properties of the growing media (Table 2.1). In late March 2015, a composite soil sample of 32 cores (3.18 cm diameter by 20 cm depth) randomly taken from the pots at each garden were collected and sent to Brookside Laboratories (New Bremen, OH) for a similar soil analysis (Table 2.1). Composite soil samples of four cores (3.18 cm diameter by 5 cm depth) were taken from the pots of eight replications of onion and pepper in fall 2014 and spring and fall 2015 and sent to Brookside Laboratories for Mehlich-3 ICP nutrient extraction as well as Mehlich-3 extractable lead testing (Mehlich, 1984; Attanayake et al., 2014). In fall 2015, EPA method 200.5 for extractable lead analysis (EPA, 1993) was used to determine soil lead content instead of the Mehlich-3 method.

Potential plant availability of nutrients and heavy metals in soil solution was determined using Plant Root Simulator probes (PRS™, Western Ag Innovation, Saskatoon, SK). These probes have a selective charged resin membrane that is placed in contact with the soil and the particles in the soil solution become attached to the resin membrane (Liang and Schoenau, 1995). The Western Ag Lab desorbs the solutes using ionically charged washes and determines NO3-N and NH4-N colorimetrically using an automated flow injection analysis system. Remaining solute contents are measured using inductively-coupled plasma spectrometry. Two vegetable crops (pepper and snap beans) were picked and three positive and three negative affinity PRS probes were inserted into the soil with the resin ranging from 5 to 22.5 cm deep in July of 2014

and May and September of 2015 for a 14 d soil incubation period. The probes were then removed, washed, and sent to Western Ag Lab for analysis.

In fall 2014 and spring and fall 2015, composite samples of four soil cores (3.18 cm diameter by 5 cm depth) from each of the eight replications of kale and tomato raised-beds at each garden were collected with a soil probe that was wiped down with alcohol between each sample for soil microbial analysis. These samples were taken from the field and frozen in a -20°C freezer for less than 90 days and sent to Ward Laboratories (Kearney, NE) for Phospholipid Fatty Acid (PLFA) analysis. PLFAs were cross-referenced with confirmed biomarkers for soil microbial functional groups of interest to estimate microbial abundance and community composition across locations and time (Frostegård and Bååth, 1996).

Comparisons of PLFA biomarker, PRS, and soil nutrient measures were performed using general linear mixed models across sampling interval, year, and garden with the nlme package (Pinheiro et al, 2015) in R (R Core Team, 2016). Similarly, linear regressions between different soil measures and environmental measures to determine association was done with *nlme* package in R. Fixed variables were block and sampling time, whereas garden and year were considered random variables. Tukey's honest significant difference separation of means for each soil measure was done using *test.HSD* function in *agricolae* package (Mendiburu, 2016) of R. All models were tested for homogeneous variances and residual normality. Appropriate transformations were used on raw data if assumptions were not met. Correlation plots of Pearson product moment coefficients from the standardized correlation matrix were made with the *corrplot* package (Wei and Simko, 2016) in R for factors and measures of PRS and microbe biomarker measures. Principal component analysis (PCA) was used to compare PRS and microbe biomarker measures to environmental measures using *princomp* function in base R.

PCA compares the maximal data variation using perpendicular vectors. This allows for the determination of most important factors of variation and their relationship to other measures and factors. The R function *biplot* was used to get biplot graphs of the first and second principal components and ovals were drawn around groupings to facilitate interpretation. Euclidean distances were done using the *dist* function in R.

Results

Raised-Bed Nutrient Concentration

Spring 2013 soil contained an average of 66 mg kg^{-1} NH_4-N and 23 mg kg^{-1} NO_3-N. By spring 2015, soil contained an average of 1.7 mg kg^{-1} NH_4-N and 39 mg kg^{-1} NO_3-N (Table 2.1). Organic matter content of the raised-bed media increased from 12.8% in 2013 to 15% in 2015 ($P = 0.0281$), while pH decreased from 8.1 to 7.6 ($P < 0.001$). Calcium and sodium concentrations decreased two-fold over the two years and potassium decreased six-fold. Cation exchange capacity (CEC) also decreased two-fold. Magnesium concentrations were unchanged while phosphorus increased two-fold between 2013 and 2015. The yard waste compost used in the soil mix had a carbon to nitrogen ratio between 18 and 22 and total nitrogen content of the compost was 2.4%. Total nitrogen contribution from the compost in each pot (0.43 m^3) was approximately 650 mg kg^{-1} and an additional 40 to 80 mg kg^{-1} was contributed from the topsoil (personal communication. Lake Street Supply, Chicago).

Bulk Soil Lead Concentration

Average soil lead levels across all gardens, determined via Mehlich-3 extraction, were not different in fall 2013, spring 2014, or fall 2014 and averaged 11.4 mg kg^{-1}. However, soil lead increased to an average of 15.2 mg kg^{-1} in spring 2015 (Fig. 2.2). In fall 2015, the EPA 200.5 extraction method was used and average soil lead level across gardens was 27.1 mg kg^{-1}.

There was no difference among gardens at any sampling interval, except in spring 2015 when lead was greatest at rural gardens St. Charles and Kuiper's, and lowest at a peri-urban garden, Cantigny (Fig. 2.2). Overall, soil lead levels were much lower than EPA hazardous exposure guidelines of 400 mg kg^{-1} lead in soil throughout the entire experiment.

Potential Plant Uptake of Heavy Metals and Nutrients

Potential plant uptake of Pb was greater, as measured by PRS probes, in soils at the most urban gardens, Growing Home and Garfield, and a peri-urban garden, Cantata, in July 2014 (Table 2.2). However, results of spring and fall soil incubations in 2015 were less conclusive, and lead availability was only different at the Cantigny location (among all gardens). Potential sulfur uptake was three times greater ($P < 0.001$) and potential P uptake was four times less ($P < 0.001$) at the Cantigny site, compared to all others, across all sampling intervals. Potential potassium uptake in July 2014 was about 10 times greater than during the 2015 sampling. In contrast, potential calcium uptake was 70% lower in July 2014 compared to 2015. Potential nitrate uptake was influenced by the interaction of sampling time and location ($P<0.001$). Pearson correlation of data from all sampling dates revealed positive correlations between Zn, Pb, P, Fe, Cu, Mn, NO_3-N, and NH_4-N ($0.14 < r < 0.83$). Sulfur was negatively correlated with P (r = -0.59), Pb (r = -0.44), and NO_3-N (r = -0.23). Calcium and Mg were negatively correlated with K (r = -0.7 and -0.35, respectively) and most environmental factors including temperature, growing degree day, vapor pressure deficit, and soil temperature. As two different crops were used, there was no effect of crop type or crop production in any solute measured (data not shown).

Principal component analysis on the combined potential uptake measures of the PRS probes and environmental factors was done and the first five principal components (PC)

accounted for 69% of variation (Table 2.3). The first PC score (23% variation explained) is explaining the variation of the environmental data compared with later sampling dates increase in Ca and the reduction in K (Table 2.3). The second PC (19% variation) is the interaction variation between S, Fe, P, Pb, Zn, and NO_3 in respect the higher S at the Cantigny garden and the reduction in P, Pb, Zn, and Mn at that garden. The third and fourth PC (12% and 9% variation respectively) are describing the variation along the gradient from urban to rural, as location gets closer to the city, B, Ca, S, and Temperature all increase, while RH, and Ozone decrease (Table 2.3). The fifth PC (6% variation) is describing more of the S dynamic to the other solutes. Biplots of the first and second PC (Fig. 2.4) reveal that sampling date explained the majority of this variation (panel a) as the grouping were easily discriminated, Euclidean distance between the groups was significant ($P < 0.001$). While garden (panel b) did not have clear discriminations, although the peri-urban site, Cantigny, had a clear grouping along the axis of S variation (no difference between Euclidean distances).

PLFA Soil Microbial Results

Total soil microbial biomass (as measured by ng g^{-1} PLFA biomass) was between 4100 and 7900 ng g^{-1} (Table 2.3). There was no effect of garden location at any sampling date for any measure of microbial biomass except for a significant interaction of garden by sampling date in bacterial and total biomass. For both bacterial and total biomass, only the fall 2014 had significant differences between sites ($P = 0.015$ and $P = 0.0037$ respectively) with the rural site, Kuipers, being significantly greater than the peri-urban site, Cantata in both biomarkers. Sampling date influenced total biomass ($P = 0.0038$), bacterial biomass ($P < 0.001$), and fungal biomass ($P = 0.0435$). Fungi to bacteria ratio and saturated to unsaturated ratio were not different across sampling dates or gardens. Fungal and mycorrhizal fungal levels were lower in spring

2015 than at either fall sampling. Levels of rhizobia ($P < 0.001$), protozoa ($P = 0.0052$), actinomycetes ($P < 0.001$), and fungi ($P = 0.0435$) were greater in fall 2015 than spring 2015 or fall 2014.

Correlation of the components (Fig. 2.5) showed nearly all PLFA biomarkers were positively correlated. The time of sampling (as ordinal numbers from 1 to 3 with one being fall 2014) was positively correlated with all PLFA measures. Temperature, growing degree days, and soil temperature (ST) were all highly correlated, so only biomarker correlation with ST will be discussed. There was a positive linear association between ST and fungi ($P = 0.0014$, $R^2 = 0.07$), protozoa ($P < 0.001$, $R^2 = 0.158$), actinomycetes ($P < 0.001$, $R^2 = 0.135$), rhizobia ($P < 0.001$, $R^2 = 0.135$), and gram positive bacteria biomarkers ($P < 0.0012$, $R^2 = 0.066$). Ozone was negatively correlated with the same PLFA biomarkers as ST, and R^2 values ranged between 0.027 and 0.051. Levels of total PLFA biomass, protozoa, actinomycetes, and fungi all increased over time. Vegetable productivity and biomass production was not significantly associated with any PLFA marker.

Principal component analysis of combined PLFA biomarkers and environmental measures revealed that a large part of the variation was differences between microbe biomarkers, and not environmental or location effects. Biplot comparison of the first two PC (Fig. 2.6) shows a clear distinction between the spring 2015 and the fall 2015 sampling date as indicated by the ovals and Euclidean distance was significantly different ($P < 0.001$) between the sampling dates, while fall 2014 sampling was not different from spring 2015 ($P = 0.345$) or fall 2015 ($P = 0.0744$) sampling dates. Location or location by sampling date did not have significant Euclidean distance separation. Positive covariation of PLFA biomass measures were explained with first

PC, which contained 46% of total variation and the second PC (19% of variation) mainly explained the variation between environmental measures.

Discussion

Lead levels appear to have increased very marginally over the three years suggesting limited aerial recontamination. Differences in fall 2015 sampling date can be explained by the different extraction method. Wharton et al., (2012) compared the Mehlich-3 test to the EPA method 3051, which is very similar to the EPA 200.5 (EPA, 2007), the EPA method is found to be more accurate and less sensitive to soil types. The Mehlich-3 extracted lead average over three samplings was about 55% of the EPA 200.5 method (13.5 to 25 mg kg^{-1} respectively), which is similar to the 53% ratio of Mehlich-3 lead extraction from various soils found in Wharton et al. (2012). Wharton et al. (2012) suggests using the Mehlich-3 method due to low cost. For this study, the Mehlich-3 test cost $11 and the EPA 200.5 cost $17 per sample. Lead levels observed in this study are well below of the critical threshold of 400 mg kg^{-1} for health hazards established by the U.S. EPA, any state, or other countries. The two most urban sites of this study were located in neighborhoods where aging housing stock is prevalent and soil lead is known to be high (Dignam et al., 2004; personal communication with Garfield Park staff). This result is in contrast to Clark et al. (2008) who reported an increase in raised bed gardens from 150 mg kg^{-1} to 336 mg kg^{-1} in 4 years from aerial deposition, and Oka et al. (2014) who found lead and zinc deposition increased two fold and eight-fold respectively between rural and urban sites in Toronto. Differences between these studies and ours could be explained by site-specific characteristics of the research area. Soil directly adjacent to raised-beds in this study was mulched with wood chips and most of the sites were at least partially surrounded by trees and fences, which could have helped to mitigate the aerial movement of contaminated aerosols.

Nonetheless, the differences among studies is stark. Potential plant uptake of heavy metals, measured via PRS probes, was elevated at urban gardens in July 2014, but this trend was not observed in either sampling interval in 2015 (Fig. 2.3). The peri-urban garden, Cantigny, had consistently low solution concentration due to the addition of sulfur in the irrigation water causing elevated pH, which is known to cause soil sorption of certain heavy metals (Harter, 1983).

Nutrient levels of soil tests and available solution nutrients from PRS sampling suggest nutrient leaching occurred over time in the raised-beds. The pots used drained well and the soil used was a sandy loam. These properties, combined with daily irrigation, likely resulted in conditions favorable for leaching. Leaching could be reduced by practicing deficit irrigation techniques. Municipal yard waste compost is generally high in salts (Hargreaves et al., 2008) and the initial soil tests indicated high salt saturation (Table 2.1). The levels of extracted K and Na dropped more than five-fold between spring 2013 and spring 2015, and plant available K from PRS sampling dropped similarly. Calcium levels decreased over two fold in the standard soil test (Table 2.1) but available Ca actually increased from 2014 to 2015 PRS test (Table 2.2). It appears that raised beds are susceptible to leaching and may present a nutrient runoff problem, although removing the excess salts in compost is beneficial to plant growth and nutrient levels were never deficient.

Soil with high sorption ability is less likely to leach P (Djodjic et al., 2004) and P levels did not increase over the sampling times. Mehlich-3 tests included a test of soil P levels and levels of 2014 tests averaged 245ppm whereas 2015 test averaged 360ppm (data not shown). The standard soil tests showed a two-fold increase in available P (Table 2.1), while available P from PRS tests (Table 2.2) did not change among samplings. While Mehlich-3 extraction is aggressive

(Eckert and Watson, 1996), most of the initial P is bound in organic material and will not be completely extracted and this may explain the increase in available P over the samplings. The standard soil tests used the Bray test, which explains why levels were less than the Mehlich-3 results. The reduction of pH over time was likely due to reduction of base saturation in the soils as minerals were leached out. The two-fold reduction of CEC can be explained by the common method of calculation which is formulated for mineralized soils, and is highly dependent on base saturation (Bache, 1976) which was altered by leaching in this study.

Soil organic nitrogen mineralization is the major source of soil nitrate needed for plant growth in compost-based soils. A net mineralization of 9-16% above initial inorganic N is expected from most compost in the first year (Hadas and Portnoy, 1994) and then each subsequent year following the mineralization is approximately halved. Mineralization between 59 and 104 mg kg^{-1} N plus about 90 mg kg^{-1} initial inorganic nitrogen resulted in between 149 and 194 mg kg^{-1} plant available N in the first year. The additional 15 cm of compost/soil mix added in 2014 had the same nutrient profile of the 2013 mixture (data not shown), resulting in plant available N levels similar to the 2013 season in the top 15 cm. In 2015, another soil sample was taken and beginning levels of nitrate were 40 mg kg^{-1}, and based on mineralization estimates from Hadas and Portnoy (1994), mineralization would be between 35 and 55 mg kg^{-1} over the season making the total N available between 75 and 95 mg kg^{-1} in 2015. All crops require nitrogen at rates of 75 to 100 mg kg^{-1} meaning 2013 and 2014 likely had sufficient available soil N, while N levels in 2015 had possible nitrogen deficiency. However, levels of available N measured via PRS probes increased from 2014 and 2015, suggesting the N mineralization rates exceeded estimates. Initial soil test lower NO_3 and higher NH_4 levels indicated an anorexic soil,

but the spring 2015 sample suggest that the soils were highly aerobic as levels of NO_3 where much higher than NH_4.

The fungi to bacteria ratio was lower than in most agriculture soils (Bailey et al., 2002), which may have been influenced by the relative age, disturbance, pH, or soil organic material of the soil (Frostegård and Bååth, 1996; McKinley et al., 2005). Temperature and soil temperature were highly correlated factors and temperature is a large driver of microbial community change and PLFA measures (Zhang et al., 2005). Ozone has been found to be negatively correlated with soil microbial biomass in rice (Chen et al., 2010), wheat (Chen et al., 2015), and native prairie (Kanerva et al., 2008) grass which is a trend observed for six PLFA biomarkers in this study. The mechanism of the effect ozone has on soil microbes not been elicited. The ozone effect may explain the fall 2014 sampling lower total and bacterial biomass markers as the peri-urban sites consistently had higher ozone levels (Table 2.3). PLFA biomass of many biomarkers in the fall samplings was greater than in the spring sampling. Spedding et al. (2004) found that time of year of sampling had a larger effect on PLFA biomarkers than tillage or crop treatments. Soil moisture was maintained near field capacity in this study and low fungi:bacterial ratio may be due to lack of water stress, which can tends to favor fungal over bacterial abundance (Brussaard et al., 2007). The ratio of saturated:unsaturated biomarkers is an indication of stress conditions in the soil (Kieft et al., 1997). The higher levels in the spring sampling time suggest more stressful conditions. There are studies where net primary productivity causes effects in soil microbe dynamics (Kaye et al., 2005; McKinley et al., 2005), but most are done in natural systems with more variable growing conditions and may explain the lack of crop biomass effects in this study. It appears that compost based raised bed microbe dynamics are influenced by time of year > microclimate factors (temperature and ozone) > location along urban gradient. The overall

increase in microbe biomass, several fungi biomarkers, and fungi:bacteria ratio as time passed a suggest a maturation of soil processes.

Conclusion

The objective of this study was to explore soil dynamics across an urban environment in a raised-bed vegetable production system. Soil lead levels, or potential plant uptake, did not increase in any of the test gardens over the three years, even in areas of Chicago with known elevated soil lead levels. Soil chemical changes occurred over time in the raised beds including leaching of minerals K, Ca, and Na, an increase in of nitrate and P, and a reduction in soil pH. Nitrogen levels, as indicated by solution levels from PRS sampling, stayed steady or increased in the media over time suggesting the compost-based media provided sufficient nitrogen fertility. Soil microbial biomass increased over time in raised-beds and was positively correlated with soil temperature and negatively correlated with ozone concentrations. Increases in total microbial biomass, various fungi biomass, and fungi:bacteria ratio suggests soil maturation over time. Results suggest the raised-bed vegetable production system used in this study provides sufficient crop nutrition and successfully mitigates crop and human exposure to heavy metals for at least three years after establishment.

Tables

	Garden	OM (%)	Total CEC (meq/100 g)	pH	P	Ca	Mg	K	Na	Base Saturation Ca (%)	Mg (%)	K (%)	Na (%)	Other (%)	H (%)	NO3-N	NH4-N	S	B	Fe	Mn	Cu	Zn
March 2013	Kuipers	13.0	21	8.1	130	2200	656	1700	220	49.9	25	20	4.4	0	0	28	88						
	St Charles	14.0	20	8.2	160	2000	615	1550	190	50.3	26	20	4.2	0	0	15	71						
	Cantigny	10.7	20	8.0	120	2200	588	1350	230	53.5	24	17	4.9	0	0	23	67						
	Cantata	12.6	20	8.2	130	2100	590	1250	170	54.4	25	17	3.9	0	0	20	43						
	Growing Home	13.8	23	8.1	180	2300	711	1750	230	49.7	26	20	4.5	0	0	32	79						
	Garfield	12.8	20	7.9	130	2050	635	1400	190	51.8	26	18	4.2	0	0	22	47						
March 2015	Kuipers	13.0	11	7.6	240	1000	446	390	80	48.3	35	9.6	3.2	3.8	0	47	1.4	23	1.6	170	6	0.76	2.7
	StCharles	17.3	11	7.9	260	1100	427	200	160	51.0	34	4.8	6.7	3.5	0	34	1.6	21	1.4	170	5	0.54	2.9
	Cantigny	15.3	11	7.5	270	1050	479	180	80	50.4	38	4.4	3.3	3.9	0	39	1.8	52	1.2	170	7	0.72	5.8
	Cantata	16.3	10	7.5	250	1050	424	160	30	54.2	36	4.3	1.4	3.9	0	38	2.3	22	1.0	160	6	0.67	3.5
	Growing Home	15.7	10	7.6	250	1050	391	230	30	54.1	34	6.3	1.5	3.8	0	36	1.8	23	1.0	170	5	0.51	2.8
	Garfield	12.8	10	7.4	240	1100	408	190	30	55.7	34	4.8	1.5	4.0	0	40	1.7	24	1.0	170	5	0.72	2.9

Table 2.1 Standard soil test analyzed at Midwest Lab Inc. (Omaha, NE). The March 2013 test was taken from random in the bulk piles before raised bed gardens were filled. March 2015 tests were 6 inch soil cores taken from 16 random raised beds from each site. All units are in mg/kg unless indicated.

	Garden	Pb	Total N	NO3-N	NH4-N	P	K	Ca	Mg	Fe	Mn	Cu	Zn	B	S	Al	Temp	Soil Temp	GDD	CO_2	RH	Ozone
								µg solute · 10cm^{-2}									*°C*	*°C*	*base 4°C*	*ppm*	*%*	*ppb*
July 2014	Kuipers	3.8	54	53	1.3	48	652	1500	480	25	2.1	0.58	6.4	0.79	40	10	20.6	22.0	238	331	72.1	12.6
	StCharles	4.2	39	38	1.4	40	296	1800	530	19	1.6	0.44	5.8	0.88	70	15	20.5	20.9	237	386	72.9	19.4
	Cantigny	3.4	70	69	1.6	10	326	1800	570	37	1.1	0.52	7.6	0.80	1100	13	20.9	21.8	243	347	70.7	19.4
	Cantata	5.5	105	104	1.0	40	918	1600	490	27	1.8	0.48	7.1	1.02	170	13	20.6	21.4	222	387	77.2	21.1
	Growing Home	10.0	88	86	1.6	60	857	1600	460	47	2.3	0.87	13.4	0.92	260	9	21.7	21.8	254	379	62.7	9.67
	Garfield	6.7	168	167	1.1	60	401	2300	560	32	2.6	0.91	9.5	0.75	320	12	22.2	21.8	262	371	61.6	9.67
May 2015	Kuipers	6.8	198	195	2.5	68	79	2400	590	24	1.2	0.60	11.1	1.60	50	11	20.9	21.7	227	373	78.7	6.19
	St Charles	7.8	250	247	2.7	74	79	2400	560	33	1.5	0.80	12.9	1.67	110	12	21.0	22.6	228	379	78.1	3.95
	Cantigny	0.9	83	81	2.3	21	29	2100	610	15	0.3	0.40	7.1	1.28	1060	12	20.7	22.5	224	387	79.2	10.4
	Cantata	5.2	196	194	2.3	64	46	2700	580	23	1.4	0.59	9.7	1.04	170	12	20.6	21.5	222	387	77.2	21.1
	Growing Home	5.4	116	114	2.5	57	28	2400	530	25	0.90	0.62	8.7	1.86	630	14	19.9	20.6	213	395	70.8	1.07
	Garfield	9.0	170	173	2.5	74	48	2600	520	46	1.7	0.96	15.3	1.07	180	11	20.6	20.7	223	397	73.6	2.01
Sept 2015	Kuipers	6.3	207	205	1.8	44	116	2300	610	22	1.6	0.48	9.3	1.01	50	9	19.0	19.1	215	389	74.2	13.0
	StCharles	9.7	254	252	2.1	55	72	2300	510	26	1.8	0.63	12.9	0.72	150	8	19.0	18.9	214	364	75.7	19.3
	Cantigny	2.3	80	78	1.7	9	36	1900	630	25	1.2	0.44	8.7	0.50	840	8	18.9	18.8	213	413	76.0	15.8
	Cantata	7.0	250	249	1.8	50	43	2500	530	54	2.4	0.66	10.8	0.65	210	9	18.9	19.3	213	413	76.0	15.8
	Growing Home	6.2	117	115	1.6	44	49	2500	500	27	1.6	0.57	9.7	0.64	190	9	18.8	19.3	211	405	66.1	2.13
	Garfield	4.7	82	81	1.2	41	33	2600	540	25	1.6	0.94	8.2	0.84	200	10	20.4	19.2	235	392	66.1	7.40

Table 2.2 PRS™ probe measurements from six test gardens in the greater Chicago, IL metro region. Plant root simulator probes are a positive and negative probe with a membrane that serves to mimic root surface and was inserted into the soil at a depth of 5 to 22.5 cm for a two week period. The probes were then analyzed at Western Ag Inc. (Saskatoon, SK). Units expressed are µg solute per 10 cm^2 probe membrane per time of burial (14 days). Temp is average temperature, Soil Temp is average soil temperature, GDD is accumulated growing degree days, RH is relative humidity, and Ozone is average daytime ozone concentration in parts per billion.

Measure	PC1	PC2	PC3	PC4	PC5
Variation (%)	23	19	12	9	6
B	0.04	-0.11	**0.37**	0.18	-0.01
Ca	**0.32**	-0.11	0.04	**0.31**	0.19
Cu	0.02	**-0.26**	-0.06	0.03	-0.12
Fe	0.06	**-0.34**	-0.04	-0.10	**-0.44**
K	**-0.33**	-0.09	-0.10	**-0.22**	-0.03
Mg	0.11	0.10	**0.24**	0.13	-0.18
Mn	0.00	**-0.33**	-0.18	-0.19	0.02
NH_4	0.16	-0.09	**0.34**	0.07	-0.09
NO_3	0.18	**-0.21**	0.18	-0.18	-0.18
P	0.08	**-0.35**	0.13	0.06	**0.43**
Pb	0.10	**-0.42**	-0.02	-0.16	-0.07
Zn	0.13	**-0.36**	0.10	-0.08	**-0.23**
S	-0.07	**0.24**	0.08	**0.22**	**-0.59**
Sample Time	**0.41**	0.08	-0.15	-0.04	0.02
Location	0.00	-0.13	**-0.33**	**0.46**	-0.17
Temperature	**-0.34**	-0.16	0.20	**0.26**	0.03
Growing Degree Day	**-0.38**	-0.15	-0.03	0.14	-0.01
Soil Temp	**-0.28**	-0.07	**0.39**	0.15	-0.04
Relative Humidity	0.16	0.14	**0.42**	**-0.26**	-0.01
VPD	**-0.21**	-0.11	-0.16	-0.05	-0.03
Ozone	-0.09	0.14	-0.02	**-0.47**	-0.16
CO_2	**0.29**	0.04	**-0.21**	0.20	-0.17

Table 2.3. Principle component scores from PRS solute measurements and environmental variables from six experimental raised bed gardens across Chicago, IL. PC1-PC5 are the principle component scores of standardized comparisons. Bolded scores are greater than 0.20 or less than -0.20. Sample times represent the three sample dates (July 2014, May 2015, and September 2015). Location is the ordinal designation of each garden from most rural (1) to most urban (6). VPD is vapor pressure deficit.

		Total Biomass	Bacteria	Gram (-)	Gram (+)	Actinomycetes	Rhizobia	Protozoa	Fungi	Mycorrhizal	Saprophytes	Undifferncniated	Fungi:Bacteria Ratio	Sat:Unsat Ratio	Soil Temp	Ozone
							ng/g biomass								*°C*	*ppb*
Fall 2014	**Kuipers**	7100	3700	1600	2100	490	72	32	880	460	420	2500	0.22	1.56	11.4	12.1
	StCharles	6500	3500	1700	1800	430	67	49	980	520	460	2000	0.28	1.04	12.3	15.0
	Cantigny	4800	2300	1000	1100	320	53	67	660	310	360	1900	0.30	1.23	12.3	24.8
	Cantata	4200	2100	1000	1100	290	60	35	590	280	310	1500	0.28	1.23	12.8	43.0
	Growing Home	5300	2800	1300	1600	400	29	31	690	360	330	1700	0.24	1.28	12.3	6.0
	Garfield	4800	2600	1200	1400	390	82	42	730	370	360	1400	0.28	1.12	12.7	2.0
Spring 2015	**Kuipers**	5700	3000	1100	1900	350	28	21	500	220	280	2200	0.16	1.85	11.3	23.9
	StCharles	6700	3700	1700	2000	450	57	38	760	300	460	2200	0.21	1.32	11.4	29.2
	Cantigny	6500	3400	1500	1900	430	83	30	670	250	420	2400	0.19	1.60	12.4	28.4
	Cantata	7300	4000	1700	2300	530	55	39	790	340	450	2400	0.20	1.40	11.6	56.4
	Growing Home	4700	2500	1000	1600	300	2.4	13	330	150	180	1800	0.13	2.07	11.5	22.9
	Garfield	5400	3000	1200	1700	390	28	19	500	230	270	1900	0.16	1.61	11.9	6.8
Fall 2015	**Kuipers**	6400	3600	2000	1600	540	110	77	900	380	510	1600	0.25	0.93	13.1	11.5
	StCharles	6700	3700	1900	1800	630	133	61	960	410	540	2000	0.26	1.08	13.1	10.9
	Cantigny	5900	3200	1500	1700	610	171	54	750	300	450	1900	0.23	1.48	13.1	21.8
	Cantata	5500	2900	1400	1400	470	91	35	660	290	370	1900	0.23	1.15	13.5	39.3
	Growing Home	6800	3900	2000	1900	680	196	73	1020	440	580	1800	0.25	1.10	14.1	7.2
	Garfield	7900	4200	2300	2000	690	181	93	1120	460	650	2400	0.26	1.08	13.6	1.5

Table 2.4: Biomass measures from phospholipid fatty acid (PLFA) determination of sampled soils from three samplings in October 2014, April 2015, and October 2015. All measures are biomass measures in ng g^{-1} soil except fungi:bacteria ratio and Sat:Unsat ratio. Fungi:bacteria ratio is the biomass of fungi compared to biomass of bacteria. Sat:Unsat ratio is the ratio of mono-saturated membrane fatty acids to unsaturated fatty acids. Soil temperature and Ozone are averages from the 30 days preceding the sampling.

Figures

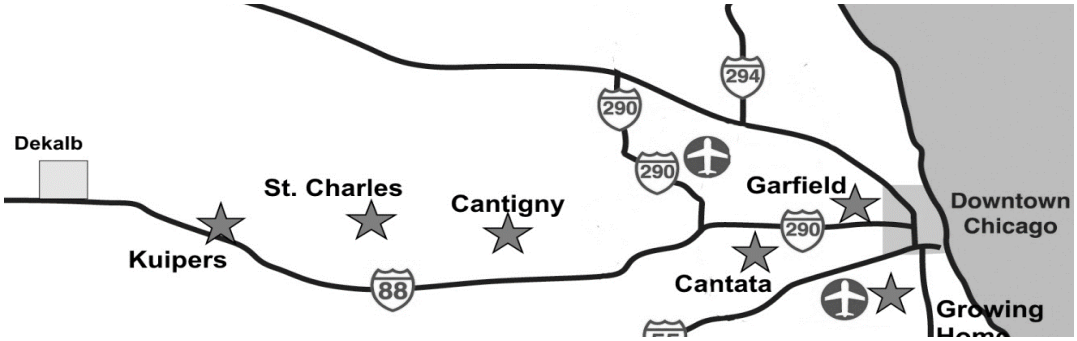

Fig. 2.1 Map of experimental garden sites across the Chicago, IL metro region. Sites are indicated by stars and adjacent labels. 'Rural' gardens included Kuipers and St. Charles, 'peri-urban' gardens include Cantigny and Cantata, and 'urban' gardens included Garfield and Growing Home.

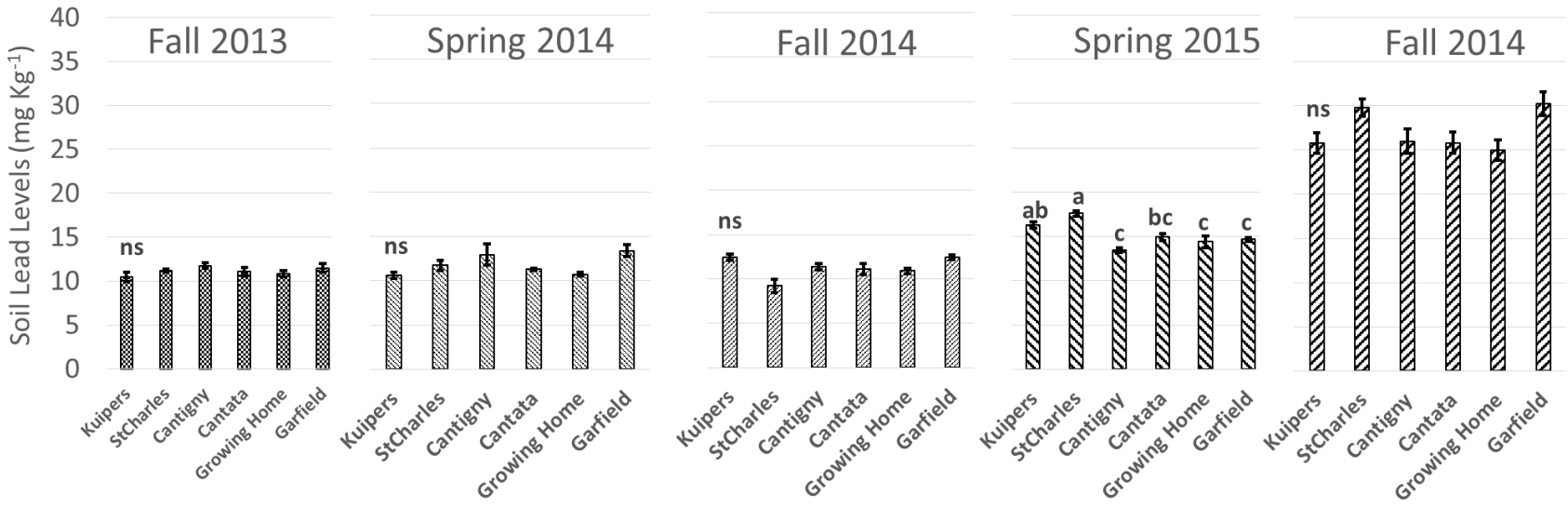

Fig. 2.2 Mehlich-3 lead soil extraction test from fall 2013 and 2014 and spring 2014 and 2015. EPA lead acid digestion 200.5 in Fall 2015. Error bars are from standard error of least squared means. Letters indicate significance of comparisons of least squared means from Tukey's honest significant difference test. ns represents no significant difference between means.

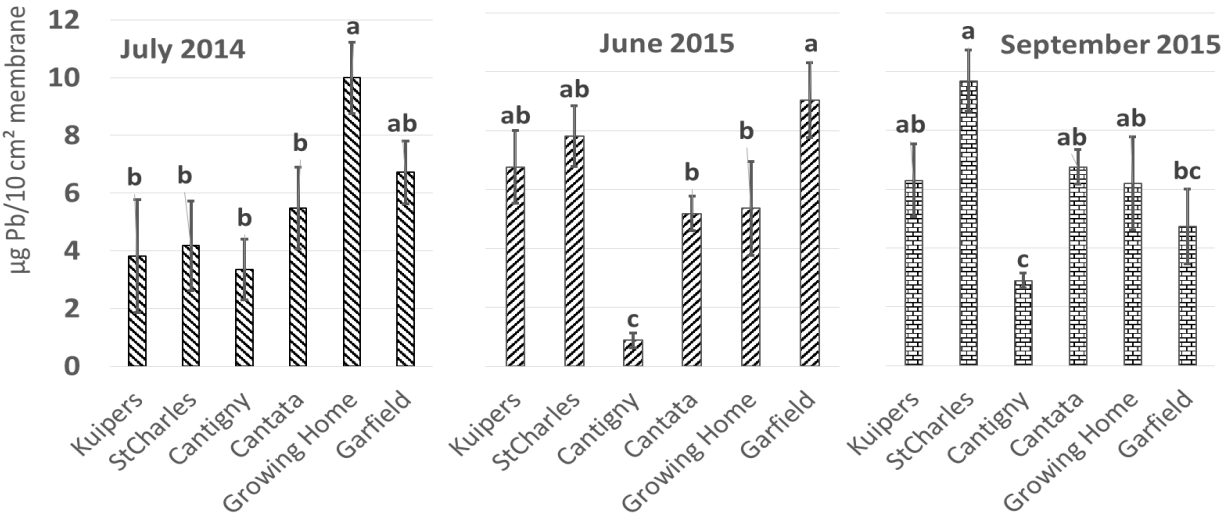

Fig. 2.3 Lead levels (µg) per 10cm^2 ion-exchange membrane from two week burials of PRS™ probes in six urban gardens across a rural to urban transect in Chicago, IL. Error bars are standard error of least squared means and letters indicate significant differences among gardens determined via Tukey's HSD test.

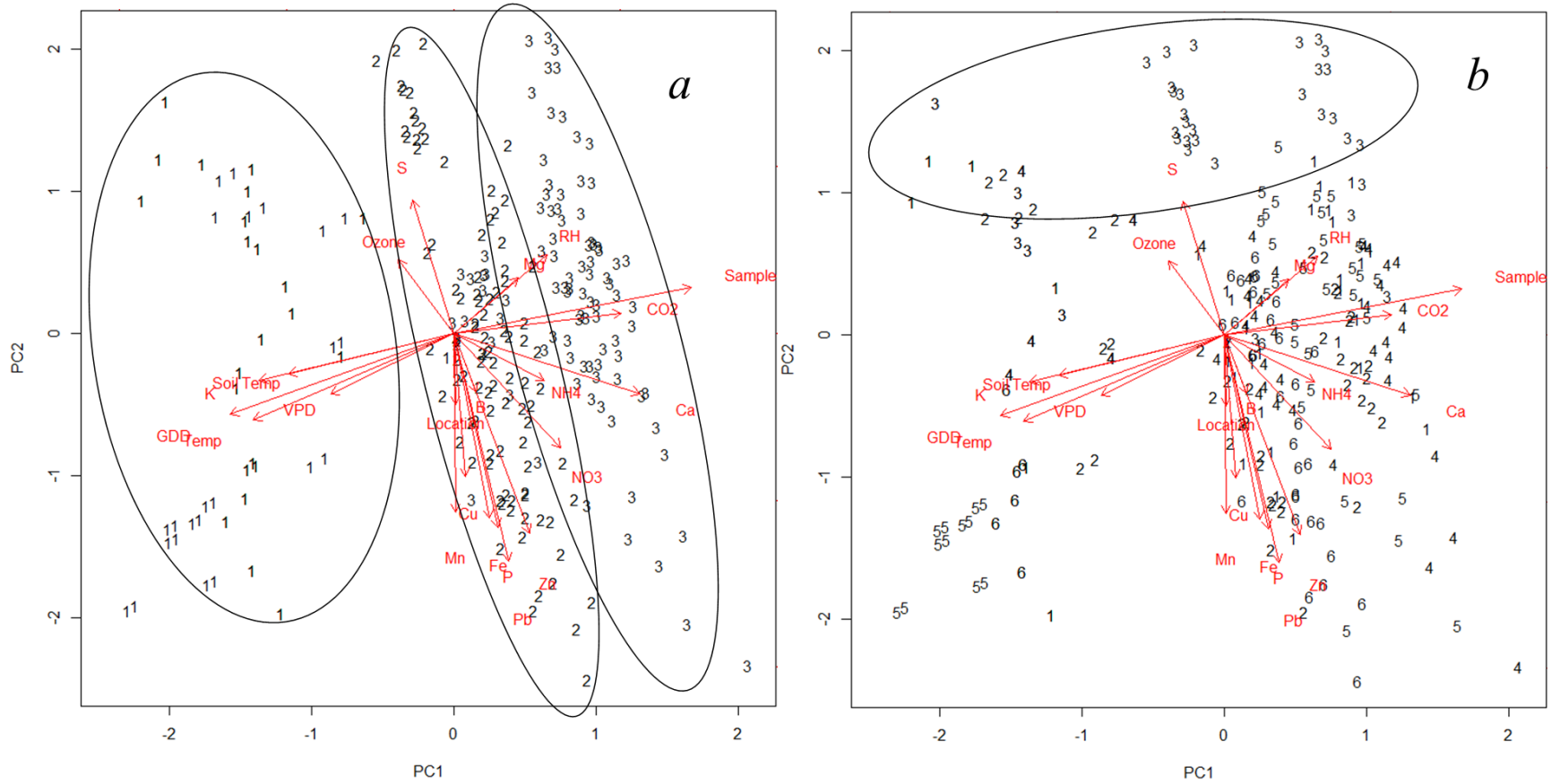

Fig. 2.4 Biplot of first two principle components of comparison of PRS™ solute analysis and environmental measures from three samplings in six raised bed gardens across Chicago, IL. The first principle component (PC1) represents 24% of variation and second represents 19% of variation (PC2). (a) Numbers indicate PRS field sampling time with 1 July 2014, 2 May 2015, and 3 September 2015. (b) Numbers indicate location from most rural, 1, to most urban, 6. Ovals represent visual groupings

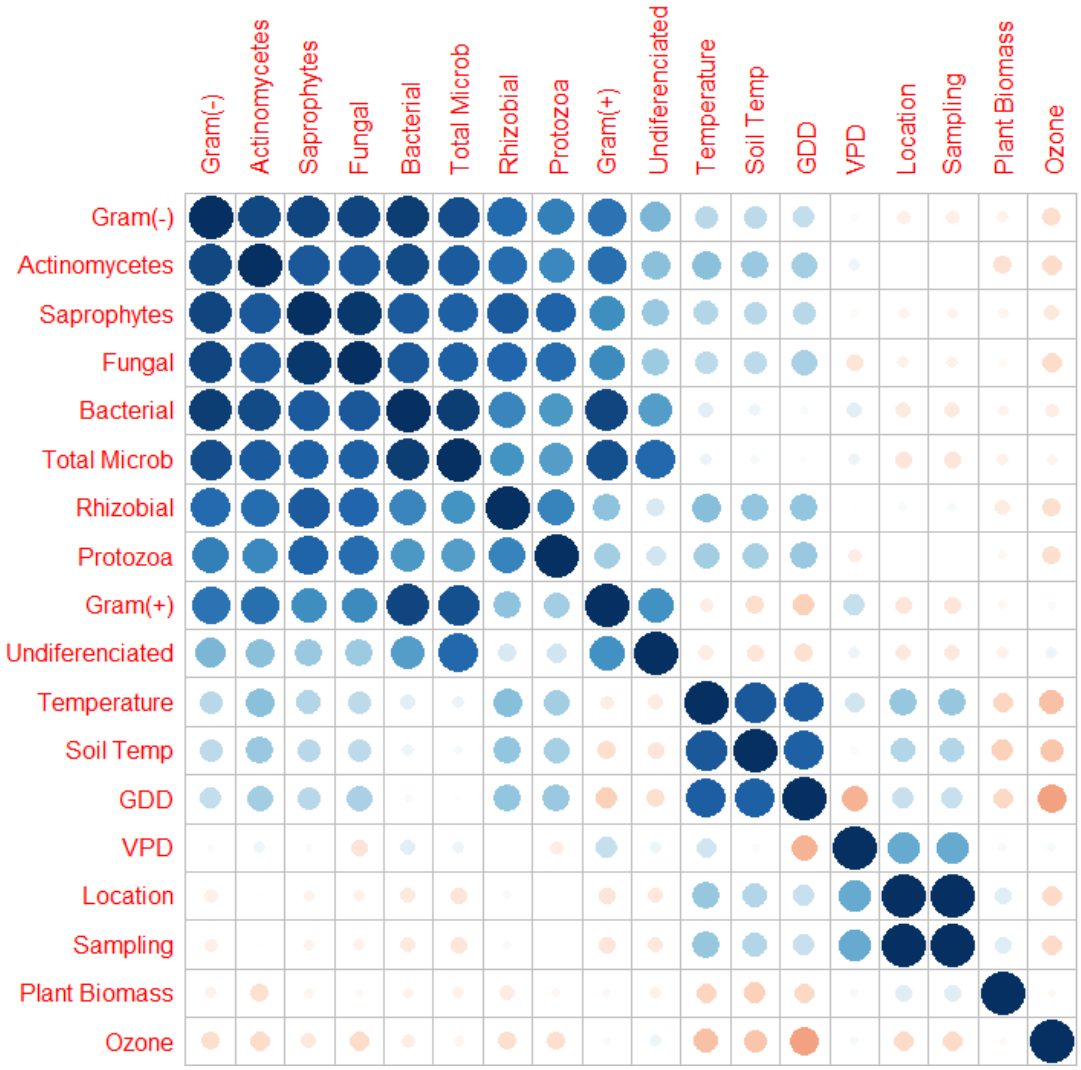

Fig. 2.5 Pearson correlation analysis of solutes from PLFA biomarker biomass estimates analysis and environmental factors from raised bed gardens in Chicago, IL. Environmental measure are averages from the 30 days prior to sampling. Sampling indicates field sampling time with 1 fall 2014, 2 spring 2015, and 3 fall 2015. Plant production is the total biomass of the plots the samples were taken from. GDD is growing degree days base 4°C, and VPD is vapor pressure deficit. Dark blue colors represent positive correlation and dark red is negative correlation.

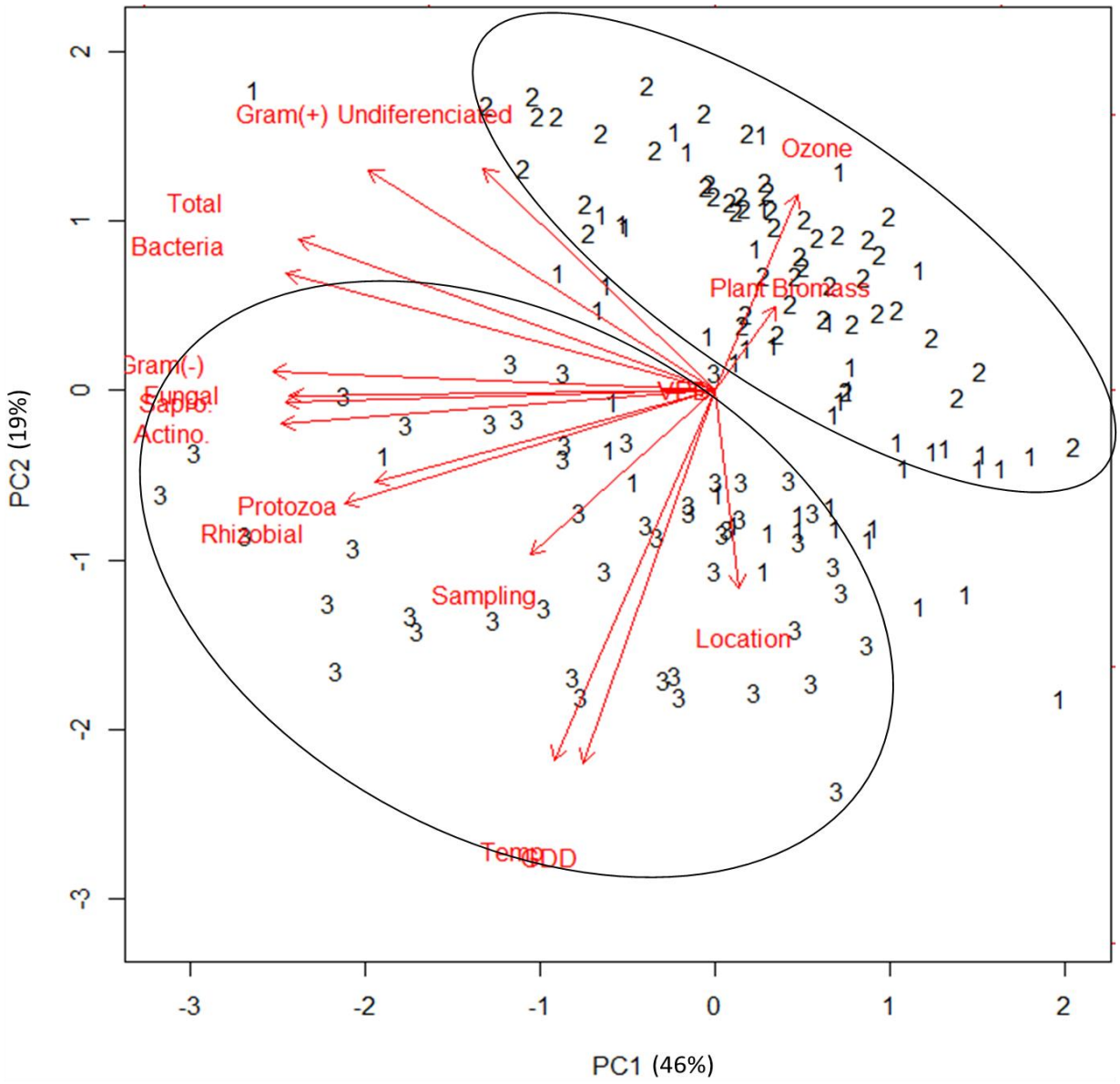

Fig. 2.6 Biplot of first two principle components (PC1 and PC2) of comparison of PLFA soil microbial analysis and environmental measures from October 2014, April 2015, and October 2015 samplings in raised bed gardens in Chicago, IL. Sample times represent the three sample dates. VPD is vapor pressure deficit, GDD is growing degree days base 4°C, Temp is Temperature (°C), Attino. is actinomycetes biomass, Sapro. Is saprophytes biomass, Total is total microbial biomass, and all other microbe measures are in estimated biomass from PLFA biomarkers.

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CHAPTER 3: FARMING IN THE CITY: DOES THE NUTRITIONAL QUALITY OF GARDEN PRODUCE CHANGE IN THE URBAN ENVIRONMENT?

Abstract

Urban agriculture is expanding, but no studies to date have quantified how the built environment affects the quality of city-grown produce. Fruit and vegetative nutrient quality (NQ) were assessed for two cultivars of seven crop species (kale, onion, bean, pepper, tomato, beet, and Brussel sprout) across six raised-bed garden gardens along a rural to urban transect of Chicago, IL. NQ tests included soluble solids (Brix), ferric reducing ability of plasma (FRAP) antioxidant assay, DPPH antioxidant assay, and Folin-Ciocalteu's total phenolic content assay (TPC) of produce extracts. Towers adjacent to gardens measured temperature, humidity, wind speed, light interception, CO_2, and ozone, which were integrated into the combined measures of growing degree day, radiant exposure, and vapor pressure deficit. For most crops, sample year and crop cultivar were the most important factors driving differences in NQ measures. Brix was greatest at rural gardens for kale, bean, and beet, which correlated to reduced yield at these locations. Brussels sprouts had greatest TPC, DPPH, and FRAP at urban gardens, and were positively correlated to temperature and yield. Kale had greatest FRAP and DPPH at a rural garden and greatest TPC at an urban garden. Beet had the greatest FRAP at peri-urban gardens. NQ measures, FRAP, TPS, and DPPH, were correlated to each other but soluble solids were not correlated to the other NQ variables. Yield and temperature were negatively correlated with Brix. TPC, FRAP or DPPH did not correlate with yield and were negatively correlated with light, temperature and vapor pressure deficite when analyzed across all crops. Principle component biplots of NQ and microclimate measures showed kale was different for higher NQ scores

compared to other crops. While variability in NQ was observed within the urban to rural gradient, there is no evidence to suggest that urban-grown produce quality is substantially different from rural-grown produce.

Introduction

Urban agriculture is seen as a means of improving access to healthy and nutritious food to urban dwellers (Mok et al., 2013). Studies have linked urban agriculture to social, economic, and health benefits in socio-economically disadvantaged neighborhoods (Brown and Jameton, 2000). In socio-economically disadvantaged urban and rural communities, consumption of fresh produce is low (Tach and Amorim, 2015), with higher rates of diabetes, obesity, and cancer in these communities (Boeing et al., 2012). Participation in gardening activities has been shown to increase consumption of fruits and vegetables (Nanney et al., 2007; Alaimo et al., 2008), and fruit and vegetable consumption is correlated with improved health and wellbeing (Slavin and Lloyd, 2012). While urban agriculture is rising in the United States and other developed countries (Mok el al. 2013), little is known about how the urban environment might influence fruit and vegetable nutritional quality.

The healthfulness of fruits and vegetables comes from a mixture of primary metabolites including fiber, carbohydrates, minerals, and vitamins and secondary metabolites including carotenoids, flavonoids, phenolic compounds, glucosinolates, and many others (Houndsome et al, 2008). Generally, fruits and vegetables are healthy because of low caloric values and high nutrients and fiber content (Liu, 2003). Each fruit or vegetable has a unique combination of primary and secondary metabolites and these are variable depending on cultivar (Butcher et al., 2013; Kleintop et al., 2016), growing conditions (Hodges and Toivonen, 2008) and growth stage (Lefsrud et al., 2007). There is also evidence that locally grown and certified organic fruits and

vegetables may have greater nutrient quality and reduced presence of pesticide residues (Mitchell et al., 2007; Barański et al., 2014). Concentrations of secondary metabolites determines, in part, the healthfulness and may enhance the marketability of a particular produce item. For example, kale was relatively unknown in the United States 10 years ago, but is now popular for its nutrient quality and is widely available in fresh markets. Other recent examples of marketing nutrient quality of produce to gain market value include pomegranate, acai berries, blueberries, and quinoa.

Measuring nutrient quality (NQ) of produce is done by several methods that assess concentrations of chemical constituents of produce. Because there are over 50,000 known and over 200,000 hypothesized secondary compounds in various metabolite families in plants (Hounsome, 2008), measures of aggregate analysis or activity of primary and secondary metabolites are used to assess relative NQ and are simpler and faster than measuring individual constituents (Singleton et al., 1999). Measurements of soluble solids, the percentage of solutes in liquid extract of produce by light refraction, and is most often associated with sugar content (Heinze and Murneek, 1940). Sample total phenols is a measure of the chemical reduction capacity of the phenolic constituents in the Folin-Ciocalteau reagent, a reagent with known specific oxidant capacity (Singleton et al, 1999). Antioxidant capacity, including ferric reducing ability of plasma (FRAP; Bernier et al., 1993) and DPPH (2,2-diphenyl-1-picrylhydrazyl; Brand-Williams et al., 1995), measures the "free radical" scavenging capacity of sample extracts to known chemical standards which is associated with relative secondary metabolite concentrations antioxidant bioactivity (Velioglu et al., 1998).

Various environmental factors play a role in plant growth and development such as temperature, light, soil conditions, nutrient and water availability, and air quality (Chapman and

Petrone, 2006). Growing conditions and abiotic stress can have substantial effects on NQ and marketability of produce (Hodges et al., 2004). Lefsrud et al. (2005) found the concentrations of the carotenoids lutein and beta-carotene in kale (*Brassica oleracea* L.) increased linearly with temperature up to 30°C, while spinach had greatest levels when grown at 15°C or less. High temperatures (above 30°C) in *Brassica oleracea* L. landraces increased sugars but decreased glucosinolates and carotenoid secondary metabolites (Rodríguez et al., 2014). In another study, accumulated heat units in tomato production was positively correlated with total phenolic and soluble solids content, but negatively correlated with dry matter and ascorbic acid content in mature fruits. Cumulative light exposure (PPFD) was positively correlated with ascorbic acid, but did not influence any other measure of tomato quality (Riga et al., 2008). In a review of secondary compound production in Brassicaceae crops, Björkman et al. (2011) demonstrated that temperature, light intensity and quality, water availability, and CO_2 can have varying effects on glucosinolate and carotenoid production. Temperature can positively influence glucosinolate concentration up to 30°C in kale, broccoli (*Brassica oleracea* italica L.), Brussels sprouts (*Brassica oleracea* cv. gemmifera), and white cabbage (*Brassica oleracea* capitate L.), but temperatures above 15°C in broccoli and kale can reduce the carotenoids beta-carotene and lutein (Pereira et al., 2002; Charron and Sams, 2004). Most studies outlined fail to demonstrate effects of light on secondary metabolites in Brassicaceae crops, but photoperiods longer than 14 hours can increase secondary metabolite production in broccoli and kale (Charron and Sams, 2004). Lastly, levels of individual glucosinolate compounds can vary with ambient CO_2 concentrations (Schonhof et al., 2006), moisture stress (Radovich et al., 2005), and biotic stress (Björkman et al., 2011). Many of these environmental factors that affect plant secondary metabolite

concentrations have been shown to vary widely across urban and peri-urban environments (Wortman and Lovell, 2013).

The objective of this study was to use aggregate secondary metabolite determination assays to assess relative NQ differences of two cultivars of seven vegetable crops in diverse environmental conditions across the greater Chicago metropolitan region. The overall goal of this study was to determine if the NQ of urban grown produce is different from produce grown in more traditional rural environments.

Materials and Methods

Field Experiment

Six experimental gardens (sites) were established in the Chicago, IL area along a latitudinal corridor close to 41° 50' N, ranging from near the city center to rural agricultural areas (Fig. 3.1). Each garden included forty 0.43 m^3 containers (Smartpot™, High Caliper Growing Systems, Oklahoma City, OK) filled with 50% leaf litter compost, 40% topsoil, and 10% sand/vermiculite mix from a single commercial batch (Lake Street Landscape Supply, Inc., Chicago IL). Test gardens were classified as urban (Garfield Park and Growing Home), peri-urban (Cantata and Cantigny), and rural (St. Charles and Kuipers) based on their proximity to the Chicago city center (Fig 3.1). Soil was maintained at or near field capacity with drip irrigation, and soil moisture was monitored with moisture sensors (200SS Watermark Sensors, Irrometer Inc, Riverside, CA). Soil samples were collected and analyzed annually to ensure adequate nutrient levels for optimal crop production. Supplemental fertilizers were not required at any point during the experiment.

Weather towers were located directly adjacent to each experimental garden and equipped with microclimate and trace gas sensors and data loggers (CR10X, Campbell Scientific, Logan,

UT). Sensors included a HMP45 temperature and relative humidity probe (Campbell Scientific, Logan, UT), cup anemometer and wind vane (Davis Instruments Corp, Hayward, CA), SP-110 pyranometer (Apogee Instruments Inc., Logan, UT), SBA-5 CO_2 infrared gas analyzer (IRGA) (PP Systems Inc., Amesbury, MA), and an F-12 toxic gas analyzer with 0-1000 parts per billion (ppb) ozone sensor (Analytical Technology, Inc., Collegeville, PA). Microclimate data were averaged or summed for the period of time from planting to when the measures were taken.

Two cultivars of seven crops were planted annually at each garden garden. Kale (*Brassica oleracea* spp. *viridis* L. cvs. *Toscano* and *Winterbor*) and onion (*Allium cepa* L. cv. *Candy* and *Red Zeppelin*) were planted in early-April, tomato (*Solanum lycopersicum L.* cvs. *Bush Goliath* and *Virginia Sweet*), pepper (*Capsicum annuum* L. cvs. *Bounty* and *Antohi Romanian*), and snap bean (*Phaseolus vulgaris* L. cvs. *R123* and *S156*) were planted in mid- to late-May, and table beet (*Beta vulgaris* spp. *vulgaris* cvs. *Merlin* and *Chioggia*) and Brussels sprout (*Brassica oleracea* spp. *gemmifera* L. cvs. *Diablo* and *Long Island*) were planted in late-July after harvest of spring crops (kale and onion) in the same pots. Eight replications of each cultivar were included in each garden. Cultivars of each crop, except snap beans, included one hybrid and one heirloom cultivar (the first listed cultivar for each crop above is the hybrid cultivar). Snap bean cultivars used were progeny of ozone resistant "Wade" and susceptible "Oregon 91" cross and showed unusual resistance (R123) and susceptibility (S156) to elevated ozone concentrations (Burkey et al., 2005).

Soluble Solids

Percent soluble solids content (Brix°) was measured in the field by extracting juices with a modified vice grip tool from a 10 g vertical wedge of the fruit/root/bulb (pepper, tomato, beet, or onion), 10 g of folded kale leaf, or two green beans. Brix° values were determined with an

auto-temperature scale, handheld digital refractometer (OPTi Digital Handheld Refractometer, Model 54, Bellingham and Stanley, Kent, UK). Two samples were taken from each plot for extraction and analysis in each of the 2014 and 2015 growing seasons. Brussels sprouts were not analyzed because the crop was harvested after the first freeze. The refractometer was zero-calibrated regularly with deionized water between each sample and was also calibrated daily with a 10% sucrose solution.

Sample Preparation

Samples for antioxidant and total phenol measures were prepared by cutting a 30 g fruit or vegetative sample from harvested material and placing it in a marked aluminum foil pouch and frozen with liquid nitrogen. The samples were then transferred into a -80°C freezer for temporary storage between 2-4 months. Samples were then freeze-dried for 7 days starting at -40°C and increasing 10°C per day until stable at 30°C in a VirTis 35L GPFD (SP Scientific, Warminster PA) freeze dryer in 2014 and Model 3600 (Freeze Dry Co. Inc., Nisswa MN) in 2015. Dried samples were then transferred into plastic bags and stored in a -20°C freezer. The samples were ground into a uniform powder using coffee grinders. A 75 mg (±2 mg) subsample was then transferred into 2 ml capped centrifuge vials, and 1.5 mL of distilled, deionized water was added to the vial. The vials were shaken for 20 minutes to homogenize samples. Next, samples sat at room temperature for 1 hour and then centrifuged for 15 minutes at 5000 rpm. Lastly, 300µL of the supernatant was decanted into a 96 well plate for use in quality analyses.

DPPH Antioxidant Assay

The DPPH antioxidant assay was done according to the method of Brand-Williams et al. (1995) with some modifications. The stock solution was prepared by dissolving 4 mg 2,2-diphenyl-1-picrylhydrazyl (DPPH, Aldrich, St. Louis, MO) with 100 mL methanol (Sigma, St.

Louis MO). Then 200µL of the DPPH solution absorbance was read at 515 nm on a spectrophotometer (ELx808, Biotek Inc., Winooski, VT) and DPPH or methanol was added until a value of 1.0 ± 0.02 units was obtained. To obtain the DPPH value, 10 µL of the extracted supernant was added into a flat-bottomed 96 well plate and 190µL DPPH solution was pippeted into the well and was allowed to react for 30 minutes at room temperature in the dark. The absorbance was then taken at 515 nm. A linear curve was obtained from a standard Trolox (Aldrich) serial dilution from 3mM to 0.094mM in each plate. The results are expressed as mM Trolox equivalent (TE) g^{-1} freeze dried material.

FRAP Antioxidant Assay

The ferric reducing ability of plasma (FRAP) antioxidant assay was done with modifications from the method of Benzie and Strain (1996). The pH 3.6 0.3M acetate buffer was prepared by adding 3.1 g $C_2H_3NaO_2 \cdot 3H_2O$ (Aldrich) and 16 ml glacial acidic acid (Sigma-Aldrich, St. Louis, MO) into 1L ddH_2O. The TPTZ solution was prepared by adding 10 mM TPMZ (2,4,6-tripyridyl-s-trazine, Sigma) in 40mM HCl. The $FeCl_3$ solution by mixing $FeCl_3 \cdot 6H_2O$ in ddH_2O to 20mM. The working FRAP reagent, which consisted of a 10:1:1 acetate buffer to TPTZ solution to $FeCl_3 \cdot 6H_2O$ solution respectively, was used within 24 hours.

To obtain the FRAP value, 10µL of the extracted supernatant was added into a flat bottomed 96 well plate and 300µL FRAP reagent was put into the well and was allowed to react for 30 minutes at room temperature in the dark. The absorbance was read at 593 nm. A linear curve was obtained from a standard Trolox serial dilution from 3 to 0.094mM ddH_2O in each plate. The results are presented mM TE g^{-1} freeze dried material

Total Phenols Assay

Total phenols were determined by a modified method from Brand-Williams et al. (1995) and Cicco et al. (2009). 10µL extracted fruit sample was pipetted into 96 well flat bottom plate and 100µL of 0.2N Folin-Ciocalteu's phenol reagent (Sigma-Aldrich) was added into the wells. This was allowed to react for 3 minutes and then 100µL 7.5% $NaCO_3$ (ThermoFisher Scientific, Waltham, MA) was added and plates were stored in the dark at room temperature for 30 minutes. A serial dilution of 10µL of gallic acid ($C_7H_6O_5$, Sigma) from 1 to $6.25x10^{-2}$ mg ml^{-1} DMSO was included in each plate. Absorbance was then read at 715 nm. Results are presented in mg gallic acid equivalents (GAE) g^{-1} freeze dried material from the standard linear curve of serial dilution.

Statistical Analysis

Analysis of variance and a general linear mixed model was used to determine the effects of year, garden location, crop, and cultivar on fruit quality measures using the nlme package (Pinheiro et al, 2015) in R (R Core Team, 2016). Fixed variables in the model included garden location, year, and cultivar, while block and sampling time were the random effects. Post hoc separation of means of measures for Tukey's honest significant difference (HSD) with a=0.05 test was done using HSD function using significance in agricolae package (Mendiburu, 2016) of R. All models were tested for homogeneous variances and residual normality. Appropriate transformations were used on raw data if assumptions were not met. Linear associations between different NQ measures and environmental factors were determined using regression analysis in the nlme package in R. Correlation plots of Pearson correlation coefficients (r) from the standardized correlation matrix were made in R and significance levels of Pearson correlation models were determined using the correlation function in R. Principle component analysis (PCA) of NQ measures, yield, and microclimate factors was done for measures TPC, FRAP and DPPH.

Soluble solids to microclimate factors were compared by PCA analysis separately. Distance between grouped factors of PCA scores was determined from ANOVA LS means of between and among group distances and differences among groups were determined via post-hoc multiple comparison using the Tukey HSD method. Correlation analysis and principle component analysis was analyzed by year because there was large inter-annual variation in all the measures.

Results

Crop Production and Environmental Differences

Crop yield was variable across year and test gardens (Table 1). In 2014, most spring and summer crops (kale, onion, beet, snap bean, and Brussels sprout) had greater yield in urban gardens, but tomato and pepper had greatest yield at peri-urban or rural gardens. In 2015, Brassicaeae crops (kale and Brussels sprout) and tomato, beet, and snap bean had greatest yield at the peri-urban garden, St. Charles, whereas onion and pepper had greatest yield in urban gardens.

Environmental conditions were variable across the urban to rural gradient (Table 3.2). Overall, temperatures were 0.9 and 1.7 °C warmer at urban gardens compared to rural during the daytime and nighttime, respectively (i.e., urban heat island effects). Season long growing degree day accumulation was 12% greater for urban gardens than rural gardens. There were an average increase of 22 frost free days in the urban gardens compared to the rural gardens. Relative humidity averaged 68% in urban gardens and 79% in rural gardens and vapor pressure deficit average was 1.04 for urban gardens and 0.56 for rural gardens. Wind speeds were greatest in rural gardens, 50% lower in peri-urban gardens, and 30% lower in urban gardens. Total radiant exposure was greatest in rural gardens, which was 8.5% greater than at urban gardens and 11% greater than at peri-urban gardens. Total sun hours in rural gardens was 11% greater than urban

gardens and 14% greater than peri-urban gardens. Transmission coefficient of the canopy was similar (about 0.93) in urban and rural gardens, but 34% lower in peri-urban gardens (0.65). Ozone was greatest at peri-urban gardens and was 50 and 70% lower at the rural and urban gardens, respectively. Carbon dioxide was greatest at the urban gardens (approximately 400 ppm) and was lowest at the rural gardens (approximately 380 ppm).

Soluble Solids

Year was significant for every crop (Table 3.3), and soluble solids in tomato, pepper, bean, and onion were greater in 2015 and greater in kale and beet in 2014. Onion and beet were the only crop with a significant difference in Brix scores between cultivars. The hybrid onion variety, Candy, had a slight increase between years (5.6 to 7.0) but the heirloom variety, Red Zeppelin, had a much larger increase (6.4 to 10.7) (Fig. 3.2). This was the only NQ measure where there was a significant variety by year interaction ($p = 0.0193$) (Fig. 3.2). Kale, beet, and bean Brix mean values were different between gardens and in all cases the rural gardens had highest Brix scores and urban sites the lowest (Fig. 3.2).

Total Phenols

Year was different for all crops in total phenolic content (TPC) (Table 3.3). Variety was significant in six of the seven crops and garden location was different in four crops. Interactions were only significant for kale and onion (Table 3.3). For bean, pepper, tomato, and beet, 2015 TPC variables were greater in 2015 than 2014 (Table 3.4). The hybrid cultivars of tomato, beet, and Brussels sprouts had greater TPC (Table 4). The heirloom variety of kale, Winterbor, had greater TPC in 2015, but the heirloom variety, Toscano, was greater in 2014. Brussels sprouts and kale had greater TPC in urban gardens, but onion TPC was greater in rural gardens (Table 5).

DPPH Antioxidant Assay

Antioxidant quenching activity of produce extracts as measured by the DPPH assay was significantly different between years for all crops ($p < 0.001$) and variety was significantly different ($p < 0.001$) for crops kale and Brussels sprout (Table 3.3). No differences among gardens were found ($p > 0.088$) in bean, tomato, pepper, and Brussels sprout. The kale hybrid variety, Winterbor, had different DPPH between a rural site and the peri-urban garden Cantata (Table 3.6). The hybrid onion variety, Candy, had greater DPPH in the rural gardens than urban (Table 3.6). Hybrid cultivars in kale and Brussels sprout had the greatest DPPH (Table 3.6).

FRAP Antioxidant Assay

Year was significant in all crops for the FRAP antioxidant assay (Table 3.3) with beet having an interaction between year and variety. Hybrid cultivars had greatest FRAP in tomato and beet and the heirloom cultivar in onion. Tomato and pepper had greater FRAP capacity in 2015 than 2014, and beans were lower in 2015 (Table 3.7). FRAP differences among gardens for kale, beet, and Brussels sprout were variable and did not follow a predictable urban to rural pattern (Fig. 3.4).

Pearson Correlation of NQ Measures, Yield, and Microclimate

Quality measures FRAP, DPPH, TPC were positively correlated ($r > 0.53$, $P < 0.0001$) in both years across crop and variety (Table 3.8). Soluble solids (Brix) was positively correlated to other NQ measures in 2015 and negatively correlated to TPC ($r = -0.12$, $P = 0.028$) in 2014. Crop yield was negatively correlated with soluble solids ($r < -0.41$, $P < 0.001$) in both years and positively correlated to TPC in 2014 and DPPH in 2015 (Table 3.8), but not correlated to other NQ measures.

Microclimate factors were highly correlated among all measures. Measures of CO_2, distance to city center, and transmission coefficient were not correlated to NQ measures. Soluble solids were negatively correlated with measures of temperature (air temperature, VPD, and GDD) and light (radiant exposure and average solar radiation) and positively correlated with relative humidity in 2014. In 2015, soluble solids were negatively correlated with light measures and GDD and positively correlated with ozone (Table 3.8). TPC, FRAP, and DPPH were either positively or not correlated to light and temperature in 2014, but mostly negatively correlated to these measures in 2015. Ozone average was positively correlated to yield and NQ measure TPC, FRAP, and DPPH in 2014 and FRAP and soluble solids in 2015 (Table 3.8).

PCA of NQ Measures and Microclimate

The nutritional quality measures TPC, FRAP, and DPPH along with microclimate measures were compared with PCA separately by year and are represented in biplots (Fig 3.4 and 3.5). Soluble solids were similarly represented with separation by year (Fig. 3.6). When comparing microclimate and NQ measures in 2014 (Fig. 3.6), the variation of TPC, FRAP, and DPPH going in the direction of the crop variation along the principle component (PC2) axis (Panel a) and kale and bean groupings were different from the other crops ($P = 0.0143$) in opposite directions. Microclimate variation (Fig. 3.4, Panel b) measures VPD, distance to city center, wind speed, and solar radiation were aligned along the PC2 axis with the garden variation and the rural gardens Kuipers and St. Charles had a different grouping from the other gardens ($P = 0.0242$). In 2015 (Fig. 3.5, Panel a) the response was similar among crops except there was no difference in the bean grouping and the kale grouping was different from all other crops ($P < 0.001$), and the majority of the NQ variation was in the first PC. The gardens in 2015 similarly were aligned to 2014 from rural to urban, but different groupings included rural site Kuipers and

urban site Growing Home ($P = 0.034$) in opposite directions of variation (Fig. 3.5, Panel b). In both years microclimate measures GDD, temperature, and radiant exposure variation was aligned opposite of the NQ measures. In 2014, the ozone variation was aligned in the axis and direction of the NQ measures.

There were no significant groupings among gardens in soluble solids to microclimate PCA comparisons (data not shown). In 2014, beets were different from the other crops in the direction of higher brix ($P = 0.0057$), whereas in 2015, kale was different ($P = 0.0371$) from tomato bean and pepper (Fig. 3.6). The axis of variation of brix was aligned with temperature, GDD, ozone, radiant exposure, and solar radiation in both 2014 and 2015.

Discussion

Measures of quality used in this study assessed a broad spectrum of secondary compounds and are not an indication of specific concentrations. Instead, the assays used in this study are generally considered to indicate concentrations by determining activity of secondary compounds for antioxidant quenching ability (FRAP and DPPH) and electron transfer capacity (TPC) (Bizuayehu et al., 2016). Prior et al. (2005) reported that no single assay can estimate the full extent of antioxidant or phenolic compounds, but in culmination the assays can provide a good estimate of bioactive secondary metabolites. In Prior et al. (2005), the TPC, DPPH, and FRAP assays are discussed and each of these assays has limitations based on specific chemistry of the reaction to secondary compounds, but each has strengths for indicating certain types of metabolites. Thaipong et al. (2006) used the same methods as in this study (excluding soluble solid method) to determine best methods for guava quality analysis and found that TPC, DPPH, and FRAP results were correlated ($0.61 < r < 0.97$, $p < 0.05$) but TPC and DPPH were less reproducible (greater variability between repetitions) than FRAP. Correlations between TPC and

FRAP in this study were similar to those reported in Thaipong et al. (2006) and Bizuayehu et al. (2016), and PCA analysis showed high covariance of these measures.

In this study, soluble solids measures had less than 30% variation among crops, while there were four fold differences among crops for DPPH and TPC and up to eight fold differences among crops for the FRAP assay. Secondary metabolite concentrations can be highly variable across crop families (up to 100-fold differences between species) and even within specific cultivars (up to ten-fold differences; Hounsome et al., 2008). Secondary metabolites are produced in response to abiotic and biotic stressors and subsequently contribute to plant defense and stress response (Edreva et al., 2008; Bartwal et al., 2012); thus, variability in NQ among years may be explained by differences in abiotic and biotic stress. In a panel of 149 bean cultivars, Kleintop et al. (2016) found that the effects of year and the interaction of year by cultivar influenced TPC in a two year genotyping experiment. Additionally, there is evidence that plant maturity effects secondary metabolite concentrations (Kozukue and Friedman, 2003; Gautier et al., 2008); however, crops sampled from each garden on the same day in this study were inevitably at different maturity levels due to differences in accumulated heat units (growing degree days) among gardens (Table 3.2).

Variety differences for NQ were greatest for beet, onion, and kale. Table beet has high levels of betalain, a carotenoid-like pigment, which affected the measure DPPH and likely the other measures to some extent. The variety, Merlin, had greater levels of betalain than Chioggia when 10X diluted samples were read at 530 nm on the spectrophotometer (data not shown). Red Zeppelin was a red onion variety and Candy was a sweet yellow variety and the additional pigmentation in Red Zeppelin (not quantified) could explain the variety differences. Green leafy vegetables, and especially kale, has been recognized for health promoting properties (Ayaz et al.,

2006). In the PCA biplots of nutrient quality (Fig. 3.4 and 3.5), kale's grouping was different from others and higher on the axis of nutrient content. The kale hybrid variety Winterbor had higher overall NQ measures than the heirloom variety Toscano, and yield of Winterbor was also greater than for Toscano (Table 3.1).

Differences between NQ measures among gardens was less pronounced than cultivar or year but some interesting trends emerged. The rural gardens had higher soluble solids in beet, bean, and kale and even though not significant, all crops but onions had the lowest Brix scores in urban gardens. The trend of higher Brix in rural gardens may be due to a relationship between yield and soluble solids; indeed, Brix ratings were negatively correlated with yield in the combined crop correlation analysis (Table 3.8) and in onion, pepper, and beet (data not shown). TPC, DPPH, and FRAP were less correlated with yield in individual crops, and where correlated, the direction of correlation was inconsistent (data not shown). The differences among sites in the PCA biplot analysis (Fig. 3.4-3.6) were mostly along the axis of microclimate variation (PC1) and less so along the axis of NQ variation (PC2). Lefsrud et al. (2005) found a positive association between yield, secondary compounds, and temperature in Winterbor kale, but a negative association in spinach. Higher yield can dilute produce nutrients, especially in non-fruiting structures such as leaves, tubers, or in florescences (Davis, 2009).

Radiant exposure integrates light interception over a period of time, and was highly correlated ($p < 0.0001$, $R^2 = 0.891$) to SR. Differences in RE between gardens is due to canopy interference (TC), haziness, or cloudiness. The lowest RE was recorded at peri-urban gardens and highest at rural gardens (Table 3.2) due to more pervasive canopy and buildings in peri-urban and urban sites. Light measures (RE and SR) were correlated to the NQ measures for 2014 and 2015 (Table 3.8) and light measures shared the axis of variation with NQ measures from

2014 (PC2) and 2015 (PC1) (Fig. 3.4 and 3.5) and Brix from both years (PC2) (Fig. 3.6). However, the direction of correlation was inconsistent in both combined correlation analysis (Table 3.8) and for individual crops (data not show). Björkman et al. (2011) found that light and photoperiod increased glucosinolates under higher light concentrations (up to 300 µmol PPFD m^{-2} s^{-1}), and light interacted with increasing temperature for increasing carotenoid concentrations. Similar results were reported by Lefsrud et al. (2006). Ohashi-Kaneko et al. (2007) found that in spinach (*Spinacia oleracea*), lettuce (*Lactuca sativa* L.), and komatsuna (*Brassica rapa* cv. *perviridis*), light quality and magnitude affected carotenoid and L-absorbic acid content. However, Riga et al. (2008) found that temperature had much greater effect on quality measures in tomato than light quantity or quality. While light did affect NQ in this study, it is difficult to elicit the exact effects due to high variability of NQ between years, crops and variety.

Temperature was highly correlated with growing degree days (R^2 = 0.896, p < 0.001) and vapor pressure deficit to relative humidity (R^2 = 0.783, p < 0.001). Temperature and VPD were higher at the urban gardens and negatively correlated with FRAP and TPC in 2015. This negative relationship suggests that NQ should have been lowest at urban gardens (Table 3.2), but an urban to rural pattern was not observed. Beet NQ measures across years were correlated with temperature and VPD (p < 0.0001), but there was no effect of temperature or VPD when years were analyzed individually (p > 0.2) (data not shown). Within year NQ measures did not correlate with temperature and VPD in bean and tomato, as well, even though the combined year analysis was significant. Because there was no correlation within year for kale, bean, and tomato, temperature correlation to NQ measures appears to be driven by inter-annual temperature variation. However, Brussels sprout TPC was correlated to temperature (R^2 = 0.09, p = 0.0028) and VPD (R^2 = 0.092, p = 0.0025) and was only sampled one year. Brussels sprout was grown

through the fall at below freezing temperatures where urban gardens had increased frost free days and higher temperatures, which may explain elevated TPC at urban gardens. There are many studies linking temperature (Angadi et al., 2000; Lefsrud et al., 2005) and VPD (Barker, 1990; Mulholland et al., 2003) to concentrations of secondary metabolites and this study found at least one example of this in Brussels sprout. Temperature was also the measure that was consistently on the same axis of variation as the NQ measures, suggesting a possible link (Fig. 3.5-3.7).

While ozone was positively correlated to NQ measure (Table 3.8) and aligned with the axis of NQ measures (Figs. 3.5-3.7), the reason may be due to the difference among crops. The ozone levels were lower during the bean growth period (May to July), and beans had the lowest NQ measures of any crop. This association may explain the positive correlation to ozone. Indeed, no crops individually were correlated to ozone (P >0.2) in 2014 or 2015. Although literature is sparse on ozone effects on fruit quality, Keutgen and Pawelzik (2008) found that a high ozone treatment during growth did not affect TPC, antioxidant capacity, or soluble solids of strawberry, but did reduce postharvest shelf life.

Conclusion

The aim of this study was to identify differences in NQ of garden crops along a rural to urban gradient across the greater Chicago, IL metro region. We found that the year of sampling and variety of the individual crop had a much greater effect than the differences between individual gardens across a diverse transect of urbanization. Even so, microclimatic factors including light, temperature, and VPD were correlated with various measures of quality, especially in early- and late-season crops (kale and Brussels sprout). Given the longer season in

the city and the higher overall NQ of the cool season crop kale, there exists an advantage for urban farmers in producing high value cool season crops earlier and later in the growing season.

Urbanization is increasing and urban agriculture is expanding in developed countries. Urban agriculture can be part of improving healthfulness of urban dwellers, especially in economically disadvantaged neighborhoods. These results show that quality of produce is minimally influenced by the unique microclimatic factors and atmospheric pollution in a built environment, and the nutritional quality of urban grown produce is comparable to that of rural produce.

Tables

		Kale		Onion		Pepper		Tomato		Bean		Beet		Brussels Sprout	
		Winterbor	*Toscano*	*Candy*	*Red Zeppelin*	*Antohi Rom.*	*Bounty*	*Bush Goliath*	*Virginia Sweet*	*R123*	*S156*	*Merlin*	*Chioggia*	*Diablo*	*Long Island*
2013	Kuipers	3.64^{b}		0.62^{a}		2.15^{a}	2.93^{a}	4.29^{c}	4.28^{bc}	1.46^{a}	0.74^{b}	0.16^{a}		1.05^{c}	
	St Charles	3.89^{ab}		0.55^{ab}		1.49^{ab}	2.92^{a}	8.18^{ab}	7.36^{ab}	1.19^{ab}	1.33^{a}	0.15^{a}		1.47^{bc}	
	Cantigny	2.82^{c}		0.37^{c}		1.87^{ab}	1.97^{ab}	6.69^{bc}	7.68^{a}	1.08^{abc}	0.86^{ab}	0.23^{a}		1.59^{bc}	
	Cantata	2.72^{c}		0.40^{c}		1.21^{b}	1.21^{b}	5.26^{bc}	5.07^{abc}	0.67^{c}	0.97^{ab}	0.20^{a}		2.23^{ab}	
	Growing Home	3.86^{ab}		0.56^{ab}		2.03^{a}	2.20^{ab}	4.66^{c}	1.88^{c}	1.05^{abc}	1.06^{ab}	0.12^{a}		1.48^{bc}	
	Garfield	4.41^{a}		0.49^{bc}		2.12^{a}	3.21^{a}	10.53^{a}	5.68^{ab}	0.85^{bc}	1.10^{ab}	0.15^{a}		2.99^{a}	
2014	Kuipers	2.24^{c}	1.08^{c}	0.27^{b}	0.29^{b}	2.78^{ab}	4.38^{ab}	6.14^{ab}	4.07^{bc}	1.24^{c}	1.59^{b}	0.26^{ab}	0.37^{a}	0.78^{b}	0.75^{a}
	St Charles	3.49^{b}	1.39^{b}	0.25^{b}	0.30^{b}	3.05^{ab}	4.78^{ab}	7.08^{a}	7.26^{a}	2.18^{a}	2.23^{b}	0.14^{c}	0.24^{bc}	0.30^{b}	0.12^{c}
	Cantigny	3.04^{b}	1.83^{b}	0.24^{b}	0.24^{b}	3.36^{a}	5.16^{a}	5.67^{abc}	4.78^{b}	1.76^{abc}	1.90^{b}	0.21^{bc}	0.29^{ab}	0.76^{b}	0.26^{bc}
	Cantata	3.36^{b}	2.58^{a}	0.24^{b}	0.25^{b}	2.61^{ab}	3.64^{bc}	4.91^{bc}	4.54^{b}	2.11^{ab}	2.31^{b}	0.15^{c}	0.18^{c}	0.29^{b}	0.15^{c}
	Growing Home	3.67^{b}	2.54^{a}	0.30^{b}	0.30^{b}	2.27^{b}	2.51^{c}	3.66^{c}	1.75^{c}	1.64^{bc}	1.901	0.28^{ab}	0.37^{a}	0.78^{b}	0.73^{ab}
	Garfield	4.55^{a}	2.62^{a}	0.44^{a}	0.40^{a}	3.47^{a}	4.93^{ab}	5.34^{abc}	4.28^{b}	2.20^{a}	3.27^{a}	0.32^{a}	0.37^{a}	1.42^{a}	1.03^{a}
2015	Kuipers	2.37^{bc}	1.34^{bc}	0.24^{bc}	0.25^{ab}	1.88^{ab}	2.93^{ab}	3.76^{ab}	7.80^{a}	1.33^{ab}	1.09^{bc}	0.43^{ab}	0.5^{a}	3.452	1.88^{b}
	St Charles	3.32^{a}	1.95^{a}	0.20^{cd}	0.23^{abc}	1.98^{ab}	3.17^{ab}	3.78^{ab}	8.30^{a}	1.80^{a}	1.63^{a}	0.46^{a}	0.58^{a}	7.71^{a}	4.40^{a}
	Cantigny	2.52^{b}	1.68^{ab}	0.17^{d}	0.18^{bc}	1.49^{abc}	2.26^{bc}	3.26^{ab}	7.45^{ab}	1.16^{b}	1.30^{abc}	0.30^{c}	0.62^{a}	3.39^{b}	2.49^{b}
	Cantata	1.79^{c}	1.21^{c}	0.19^{cd}	0.17^{c}	1.11^{c}	1.65^{c}	4.07^{a}	5.31^{b}	0.59^{c}	0.60^{d}	0.26^{c}	0.16^{b}	4.07^{b}	2.38^{b}
	Growing Home	2.66^{ab}	1.75^{ab}	0.28^{ab}	0.27^{a}	2.06^{a}	3.47^{a}	3.38^{ab}	7.77^{a}	1.73^{a}	1.38^{ab}	0.34^{bc}	0.52^{a}	3.35^{b}	2.18^{b}
	Garfield	2.54^{b}	1.79^{a}	0.31^{a}	0.23^{abc}	1.42^{bc}	2.36^{bc}	2.76^{b}	6.49^{ab}	1.01^{bc}	0.90^{cd}	0.46^{a}	0.54^{a}	4.86^{b}	4.25^{a}

Table 3.1 Yields of crops and cultivars across three years from six gardens across the Chicago, IL metro region. Sites within each year are arranged from top to bottom according to distance to city center (rural to urban). Yield data are presented as fresh kg/plot, except beets and onions which are fresh g/plant and Brussels sprouts which are total biomass/plot. Means were separated by variety within site within year from linear mixed model estimates and using the Tukey HSD means separation. Interactions of variety, site, and year were significant across most crops.

	Location	Temperature	Relative Humidity	Wind	CO_2	Ozone	AOT40	Vapor Pressure	GDD (10°C)	GDD (4°C)	Frost Free Days	Transmission Coefficient	Radiant Exposure	Sun Hours	Distance to City
		°C	*%*	*m s⁻¹*	*ppm*	*ppb*		*kPa*					*J m⁻²*		*km*
2014	Kuipers	15.3	75.1	2.14	361	23.1	60306	0.529	1552	2539	197	0.96	3798	1620	77.5
	St Charles	15.5	73.7	1.56	382			0.574	1596	2587	186	0.91	3809	1613	60.9
	Cantigny	15.8	73.4	0.89	389	29.5	51173	0.592	1635	2639	186	0.72	3565	1464	43.5
	Cantata	16.0	70.4	0.93	397			0.651	1647	2661	186	0.57	3442	1315	18.2
	Growing Home	16.5	64.5	1.04	397			0.771	1715	2743	199	0.88	3604	1508	11.2
	Garfield	16.9	67.0	1.41	398	17.1	37015	0.747	1788	2827	201	0.98	3575	1466	7.5
2015	Kuipers	16.3	75.0	2.04	390	11.2	2100	0.549	1694	2750	176	0.96	3828	1414	77.5
	St Charles	16.3	74.6	1.30	379	13.1	6349	0.568	1717	2770	176	0.91	3664	1357	60.9
	Cantigny	16.5	73.9	0.82	398	18.5	9722	0.592	1730	2794	176	0.72	3362	1243	43.5
	Cantata	16.8	71.3	0.75	407	34.2	39771	0.660	1782	2854	177	0.57	3243	1185	18.2
	Growing Home	16.7	61.7	0.97	401	2.1	268	0.843	1724	2805	199	0.88	3455	1296	11.2
	Garfield	17.5	65.1	1.36	399	7.8	2451	0.809	1888	2984	224	0.98	3459	1293	7.5

Table 3.2 Season average and accumulated measures calculated from environmental data collected at each of six gardens across the Chicago, IL metro region. GDD is growing degree days with base temperature indicated. Frost free days is the total days between the last and first frost. Transmission coefficient is calculated from fish eye photo analysis. Radiant exposure is the integration of the light irradiance measures. Sun hours is a measure of total daytime (0500 to 1900) hours where solar radiation is above 65% of maximum radiation. AOT40 is sum of part per billion hourly ozone average minus 40 if ozone average is over 40 ppb (Σ(ppb h – 40)). The Distance to city is a measure from the same point in downtown Chicago.

Crop	Brix°	TPH	DPPH	FRAP
Kale				
Year	2.24E-6***	<1E-16***	1.84E-5***	<1E-16***
Garden	1.81E-9***	0.00653**	0.888^{ns}	0.605^{ns}
Variety	0.843^{ns}	0.0462*	6.69E-8***	<1E-16***
Year*Garden	0.051^{ns}	0.0463*	0.949^{ns}	0.026*
Garden*Variety	0.615^{ns}	0.00468**	0.0216*	2.34E-7***
Garden*Variety*Year	0.439^{ns}	0.583^{ns}	0.0245*	0.871^{ns}
Onion				
Year	<1E-16***	[1]	[1]	[1]
Garden	0.616^{ns}	0.0396*	0.146^{ns}	0.0961^{ns}
Variety	<1E-16***	<1E-16***	9.87E-16***	<1E-16***
Year*Garden	0.0523^{ns}	[1]	[1]	[1]
Garden*Variety	2.69E-10***	0.0159*	6.18E-5***	0.689^{ns}
Garden*Variety*Year	0.092^{ns}	[1]	[1]	[1]
Bean				
Year	8.72E-4***	0.00415**	2.36E-6***	3.01E-4***
Garden	0.00473**	0.681^{ns}	0.114^{ns}	0.0644^{ns}
Variety	0.872^{ns}	1.31E-6***	4.43E-9***	4.74E-4***
Year*Garden	0.570ns	0.770^{ns}	0.304^{ns}	0.189^{ns}
Garden*Variety	0.910^{ns}	0.468^{ns}	2.04E-5^{ns}	0.383^{ns}
Garden*Variety*Year	0.671^{ns}	0.599^{ns}	0.891^{ns}	0.223^{ns}
Pepper				
Year	<1E-16***	1.81E-11***	1.76E-9***	4.74E-9***
Garden	0.133^{ns}	0.333^{ns}	0.218^{ns}	0.0539^{ns}
Variety	0.424^{ns}	0.685^{ns}	0.266^{ns}	0.2221^{ns}
Year*Garden	0.163^{ns}	0.433^{ns}	0.395^{ns}	0.154^{ns}
Garden*Variety	0.578^{ns}	0.522^{ns}	0.45^{ns}	0.184^{ns}
Garden*Variety*Year	0.704^{ns}	0.599^{ns}	0.599^{ns}	0.085^{ns}
Tomato				
Year	<1E-16***	<1E-16***	6.83E-6***	0.00441**
Garden	0.123^{ns}	0.190^{ns}	0.423^{ns}	0.978^{ns}
Variety	0.0739^{ns}	0.0141*	0.613^{ns}	0.00293**
Year*Garden	0.396^{ns}	0.635^{ns}	0.390^{ns}	0.246^{ns}
Garden*Variety	0.772^{ns}	0.133^{ns}	0.968^{ns}	0.605^{ns}
Garden*Variety*Year	0.704^{ns}	0.906^{ns}	0.871^{ns}	0.591^{ns}
Beet				
Year	8.58E-4***	<1E-16***	[2]	0.508^{ns}
Garden	0.00279**	0.129^{ns}	[2]	0.0488*
Variety	7.27E-8***	<1E-16***	[2]	<1E-16***
Year*Garden	0.0617^{ns}	0.050^{ns}	[2]	0.0188*
Garden*Variety	0.140^{ns}	0.788^{ns}	[2]	0.780^{ns}
Garden*Variety*Year	0.0542^{ns}	0.0573^{ns}	[2]	0.789^{ns}
Brussels Sprout				
Garden	[3]	7.90E-6***	0.088^{ns}	0.0261*
Variety	[3]	<1E-16***	2.82E-14***	<9.4E-9***
Garden*Variety	[3]	0.142^{ns}	0.533^{ns}	0.0104*

Table 3.3 Analysis of variance *p*-values from mixed models of quality measures from sampled produce of six gardens across a rural to urban gradient in Chicago, IL. Brix scores are from refractometry of extracted juices. FRAP and DPPH are assays measuring antioxidant scavenging and TPC is the total phenolic content assay.
[1] Onion samples were lost from 2014.
[2] The DPPH assay could not be read in beets due to interference of betaine.
[3] Brix readings could not done in Brussel sprouts.
*, **, *** Significant at P ≤ 0.05, 0.01, or 0.001, respectively.

Crop	Variety	
Kale	Winterbor[1]	Toscano[1]
2014[1]	45.0	37
2015[1]	54.5	73.2
Onion	Candy[1]	Red Zeppelin[1]
2015	26.8 ±0.77	40.2 ±1.04
Snap Bean	R123[a]	S156[b]
2014[b]	18.6 ±0.57	16.4 ±0.48
2015[a]	20.2 ±0.40	17.7 ±0.39
Pepper	Bounty[ns]	Antohi Rom.[ns]
2014[b]	45 ±1.12	45 ±1.00
2015[a]	63.8 ±1.53	62.7 ±2.36
Tomato	Bush Goliath[a]	Virginia Sweet[b]
2014[b]	21.3 ±0.48	20.2 ±0.68
2015[a]	31.7 ±0.73	29.2 ±0.63
Beet	Merlin[a]	Chioggia[b]
2014[b]	33.9 ±0.67	20.2 ±0.41
2015[a]	55.2 ±2.23	28.7 ±2.01
Brussels Sprout	Diablo[a]	Long Island[b]
2015	48.5 ±0.68	38 ±0.88

Table 3.4: Total phenolic content assay (TPC) results in mmol Gallic acid equivalent (GAE) per g dry fruit weight (DW) plus or minus standard error of measures. Letters indicate differences between variety or year based on Tukey's honest significant difference (α = 0.95).
[1] Kale and onion had significant interactions of garden by variety and variety by year.

Crop	Variety	Kuipers	St. Charles	Cantigny	Cantata	Growing Home	Garfield
Kale				*mmol GAE per g DW*			
2014	Winterbor[a]		29.7 ±4.23[b]	48.1 ±2.79[a]	45.9 ±3.03[a]	50.4 ±4.16[a]	51.1 ±3.13[a]
	Toscano[b]		36.2 ±3.96[ns]	37.6 ±2.74	36.2 ±2.18	37.2 ±2.57	37.9 ±3.01
2015	Winterbor[b]	54.3 ±2.92[ns]	56.3 ±3.65	49.6 ±2.87	49.9 ±3.46	57.2 ±2.86	59.6 ±2.87
	Toscano[a]	77.5 ±4.66[ns]	73.8 ±1.68	74.7 ±3.22	67.3 ±5.73	65.7 ±3.96	79.5 ±2.39
Onion							
2015	Candy[b]	28.2 ±1.57[ab]	30.6 ±2.17[a]	28 ±1.88[ab]	26.7 ±1.31[ab]	23.9 ±1.05[b]	23.6 ±2.28[b]
	Red Zeppelin[a]	40.9 ±3.3	38 ±2.32	40 ±2.22	44 ±2.62	37 ±1.97	41.5 ±2.62
Brussels Sprout							
2015		38.9 ±2.33[b]	41.7 ±1.91[ab]	43.7 ±1.48[ab]	43.8 ±1.68[ab]	45 ±1.08[a]	46.4 ±2.19[a]

Table 3.5: Total phenolics assay (TPC) results in mmol Gallic acid equivalent (GAE) per g DW plus or minus standard error of measures. Letters indicate differences among gardens and cultivars based on Tukey's honest significant difference (α = 0.05).

Crop	Variety	
Kale	Winterbor [a]	Toscano [b]
2014[a]	97 ±2.74	75.1 ±2.7
2015[b]	75.1 ±1.04	51.8 ±1.28
Onion[1]	Candy	Red Zeppelin
2015	38.4 ±0.78	50 ±1.05
Snap Bean	R123 [a]	S156 [b]
2014[b]	20 ±0.71	17.1 ±0.43
2015[a]	23.2 ±0.59	19.3 ±0.54
Pepper	Antohi Rom. [ns]	Bounty [ns]
2014[a]	73.6 ±2.66	70.7 ±2.67
2015[b]	67.2 ±1.26	65.8 ±1.26
Tomato	Bush Goliath [ns]	Virginia Sweet [ns]
2014[b]	34.4 ±2.41	38.2 ±3.51
2015[a]	56.6 ±1.03	51.4 ±1.35
Brussels Sprout	Diablo [a]	Long Island [b]
2015	38.4 ±0.73	26.2 ±1.15

Table 3.6: DPPH assay results in mmol Trolox equivalent (TE) per g DW plus or minus standard error of measures. Letters indicate differences between variety or year based on Tukey's honest significant difference (α = 0.95).
[1] Onion had significant garden by variety interaction.

Crop	Variety	
Kale [1]	Winterbor	Toscano
2014	83.6 ±2.76	53.4 ±2.43
2015	60.34 ±1.49	33.9 ±1.04
Onion	Candy [b]	Red Zeppelin [a]
2015	24.9 ±0.88	48.7 ±1.82
Snap Bean	R123 [a]	S156 [b]
2014 [b]	14.1 ±0.89	11.9 ±0.77
2015 [a]	17.0 ±0.56	14.3 ±0.44
Pepper	Antohi Rom. [ns]	Bounty [ns]
2014 [b]	43.4 ±1.39	42.9 ±1.34
2015 [a]	52.3 ±1.94	57.8 ±2.06
Tomato	Bush Goliath [a]	Virginia Sweet [b]
2014 [a]	18.2 ±0.53	16.7 ±0.71
2015 [b]	17.2 ±0.43	16.2 ±0.6
Beet [1]	Merlin [a]	Chioggia [b]
2014	84.7 ±1.7	15.3 ±1.06
2015	90.8 ±2.37	13.0 ±0.61
Brussels Sprout [1]	Diablo	Long Island
2015	57.9 ±1.14	44.7 ±1.9

Table 3.7: FRAP assay results in mmol Trolox equivalent (TE) per g DW plus or minus standard error of measures. Letters indicate differences between variety or year based on Tukey's honest significant difference (α=0.05). [1] Kale, beet, and Brussels sprout had significant interactions of garden by variety or garden by year.

	TPC	FRAP	DPPH	Brix°	Yield	CO_2	Ozone	Wind	R.H.	V.P.D.	Temp	GDD	S.R.	R.E.	T.C.
FRAP	0.73 ***														
DPPH	0.7 ***	0.76 ***													
Soluble Solids (Brix°)	-0.12 *	-0.1 .	0.11 .												
Crop Yield	0.26 ***	0.01	0.07	-0.46 ***											
CO_2	-0.01	0	0.01	0.05	0.1 *										
Ozone Average	0.34 ***	0.22 ***	0.42 ***	-0.07	0.05	0.11 *									
Wind Speed	0.13 **	0.08 *	0.12 *	-0.01	0.06 .	0.19 ***	-0.03								
Relative Humidity	-0.3 ***	-0.1 *	-0.25 ***	0.32 ***	-0.14 **	0.5 ***	-0.35 ***	0.13 **							
Vapor Pressure Deficit	0.23 ***	-0.03	0.01	-0.54 ***	0.39 ***	-0.42 ***	0.08 *	-0.34 ***	-0.83 ***						
Temperature	-0.05	-0.21 ***	-0.32 ***	-0.4 ***	0.49 ***	0.01	-0.45 ***	-0.33 ***	0.18 ***	0.4 ***					
Growing Degree Days	0.38 ***	0.02	0.07	-0.71 ***	0.76 ***	-0.02	0.12 **	0.05	-0.34 ***	0.65 ***	0.61 ***				
Solar Radiation	0.38 ***	0.06 .	0.22 ***	-0.59 ***	0.57 ***	0.08 *	0.26 ***	0.5 ***	-0.29 ***	0.28 ***	0.07 *	0.74 ***			
Radiant Exposure	0.46 ***	0.11 *	0.38 ***	-0.63 ***	0.69 ***	0.02	0.36 ***	0.31 ***	-0.42 ***	0.48 ***	0.21 ***	0.89 ***	0.94 ***		
Transmission Coefficient	-0.02	-0.01	-0.05	0.03	0.06	-0.15 **	-0.64 ***	0.64 ***	0.01	-0.02	0.02	0.03	0.18 ***	0.05	
Distance to City Center	-0.05	0.01	-0.06	0.12 *	0.04	0.39 ***	-0.13 **	0.57 ***	0.74 ***	-0.77 ***	-0.09 *	-0.08 *	0.31 ***	0.09 *	0.2 ***

(a)

	TPC	FRAP	DPPH	Brix°	Yield	CO_2	Ozone	Wind	R.H.	V.P.D.	Temp	GDD	S.R.	R.E.	T.C.
FRAP	0.75 ***														
DPPH	0.66 ***	0.53 ***													
Soluble Solids (Brix°)	0.13 *	0.3 ***	0.16 **												
Crop Yield	0.01	-0.07	0.15 **	-0.41 ***											
CO_2	0.03	0.01	0.02	0.08 .	0.01										
Ozone Average	0.1 *	0.13 **	-0.04	0.16 ***	-0.07 .	0.47 ***									
Wind Speed	0.11 *	0.22 ***	0.04	0.01	0.01	0.2 ***	-0.23 ***								
Relative Humidity	-0.12 *	-0.16 **	-0.03	-0.01	0.1 *	0.74 ***	0.35 ***	0.3 ***							
Vapor Pressure Deficit	-0.13 **	-0.14 **	0	-0.02	-0.03	-0.45 ***	-0.39 ***	-0.5 ***	-0.62 ***						
Temperature	-0.28 ***	-0.35 ***	0.04	-0.05	0	0.07 *	-0.23 ***	-0.33 ***	0.14 ***	0.67 ***					
Growing Degree Days	-0.4 ***	-0.58 ***	-0.29 ***	-0.24 ***	0.31 ***	0.04	-0.2 ***	-0.26 ***	0.19 ***	0.37 ***	0.6 ***				
Solar Radiation	-0.09 *	-0.14 **	0.31 ***	-0.21 ***	-0.11 *	0.11 **	-0.29 ***	0.32 ***	0.34 ***	0.01	0.47 ***	-0.02			
Radiant Exposure	-0.41 ***	-0.63 ***	-0.26 ***	-0.27 ***	0.28 ***	0.06 .	-0.24 ***	0.13 **	0.4 ***	-0.1 *	0.26 ***	0.78 ***	0.25 ***		
Transmission Coefficient	-0.02	0.02	0.01	-0.06	0.08 *	-0.16 ***	-0.78 ***	0.65 ***	-0.12 **	0.04	-0.03	0.01	0.31 ***	0.2 ***	
Distance to City Center	-0.03	0.03	0.02	0.05	0.05	0.4 ***	0.04	0.65 ***	0.81 ***	-0.63 ***	-0.03	-0.05 .	0.44 ***	0.28 ***	0.24 ***

(b)

Table 3.8 Pearson correlation coefficient for fruit quality, yield, and microclimate measures from seven crops in six gardens across a rural to urban gradient in Chicago, IL. TPC is total phenolic assay, FRAP is FRAP antioxidant capacity assay, DPPH is DPPH antioxidant capacity assay, Brix° is percent soluble solids, abbreviations along the top are spelled out on the first column on the left. Panel a is comparisons from 2014 measures. Panel b is from 2015. .,*, **, *** Significant at P ≤ 0.1, 0.05, 0.01, or 0.001, respectively.

Figures

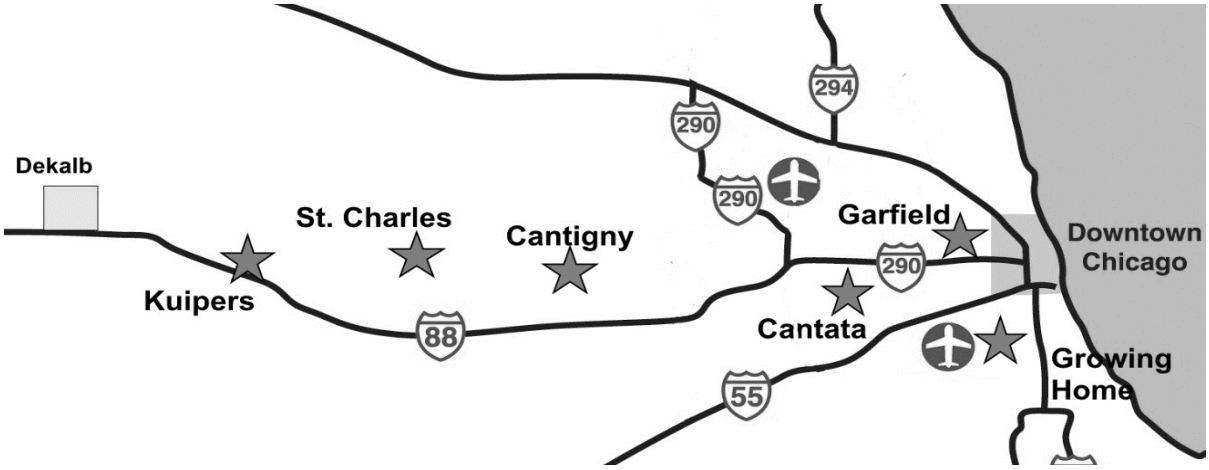

Fig. 3.1 Map of experimental garden sites across the Chicago, IL metro region. Sites are indicated by stars and adjacent labels. 'Rural' gardens included Kuipers and St. Charles, 'peri-urban' gardens include Cantigny and Cantata, and 'urban' gardens included Garfield and Growing Home.

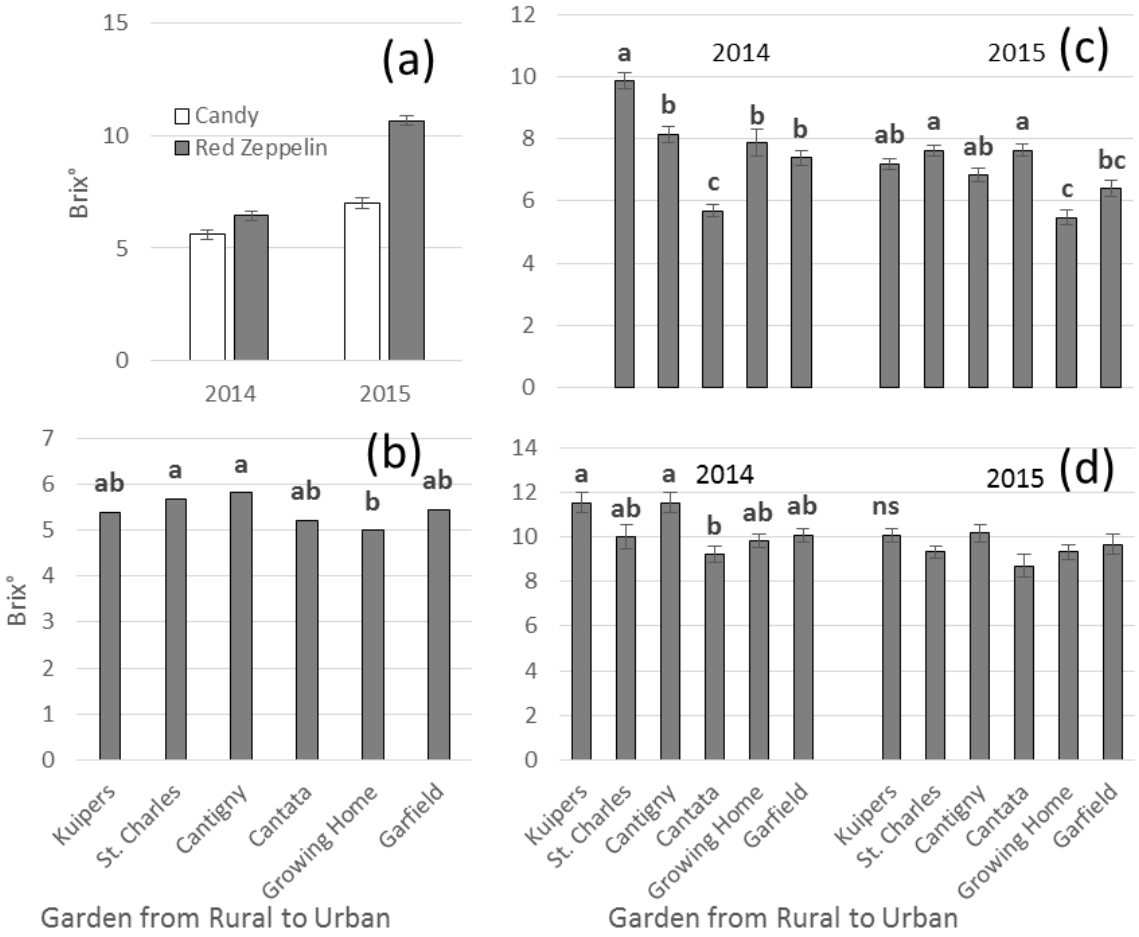

Fig. 3.2: Soluble solids of sampled produce from gardens across a rural to urban gradient of Chicago, IL as measured in percent soluble solids of solution (Brix°). Letters indicate differences between variety or year based on Tukey's honest significant difference (α = 0.05) and ns signifies no significant difference. Error bars are standard error of least square means. Bean least squared means were back-transformed after log transformation for normality of variance and error values could not be back-transformed. (a) Onion Brix variety and year comparison. (b) Bean Brix garden analysis. (c) Kale Brix garden within year. (d) Beet Brix garden within year.

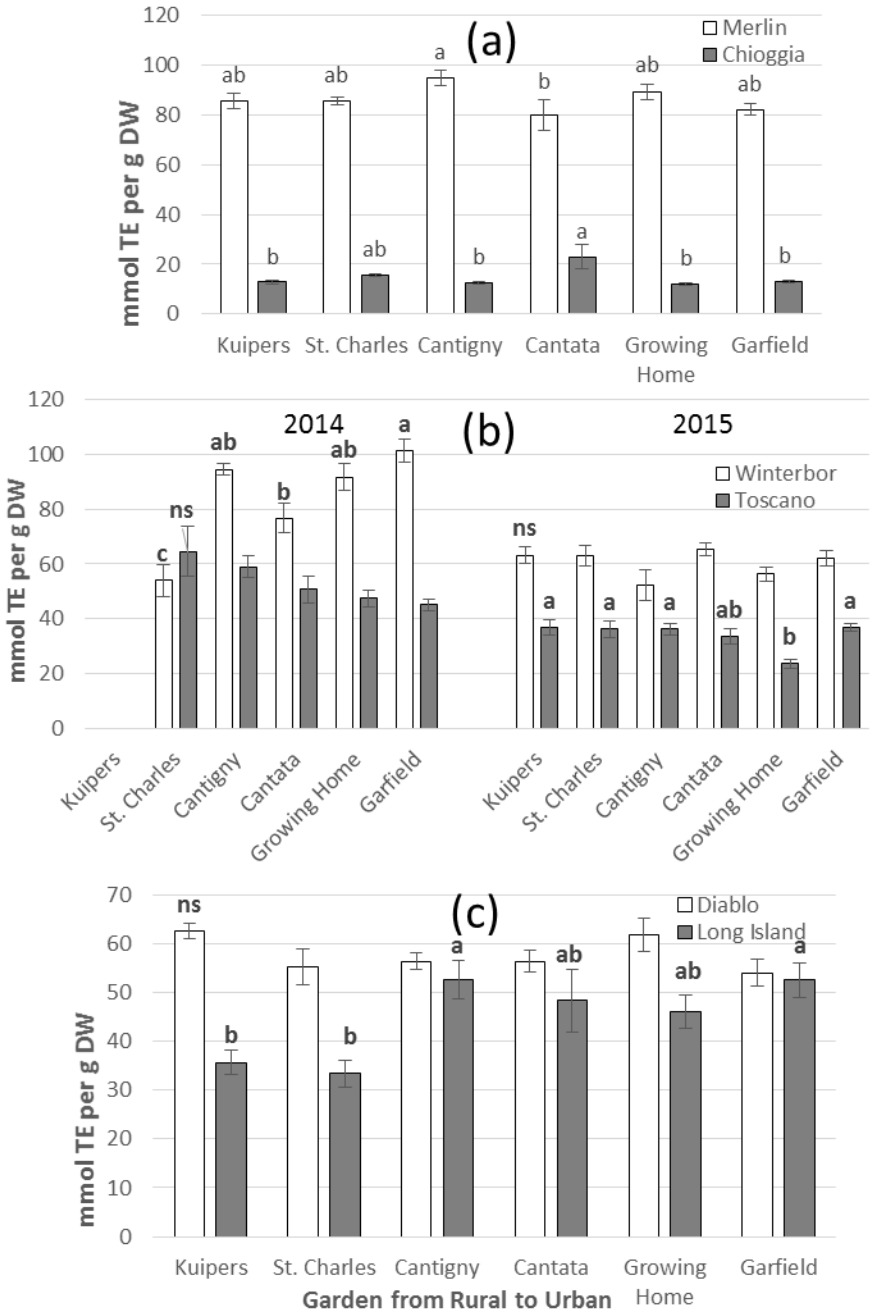

Fig. 3.3 Beet, Brussels sprout, and kale FRAP antioxidant scavenging assay measures in mmol Trolox equivalent (TE) per gram dry fruit weight (DW). Samples are taken from six gardens along a rural to urban gradient of Chicago, IL. Error bars are the standard error of the least squares means. Letters represent differences in means from Tukey's honest significance test (α=0.05). Panels (a) is the 2014 and 2015 combined beet FRAP measures, (b) is kale FRAP variety within garden within year measures, and (c) is the 2015 Brussels sprout FRAP.

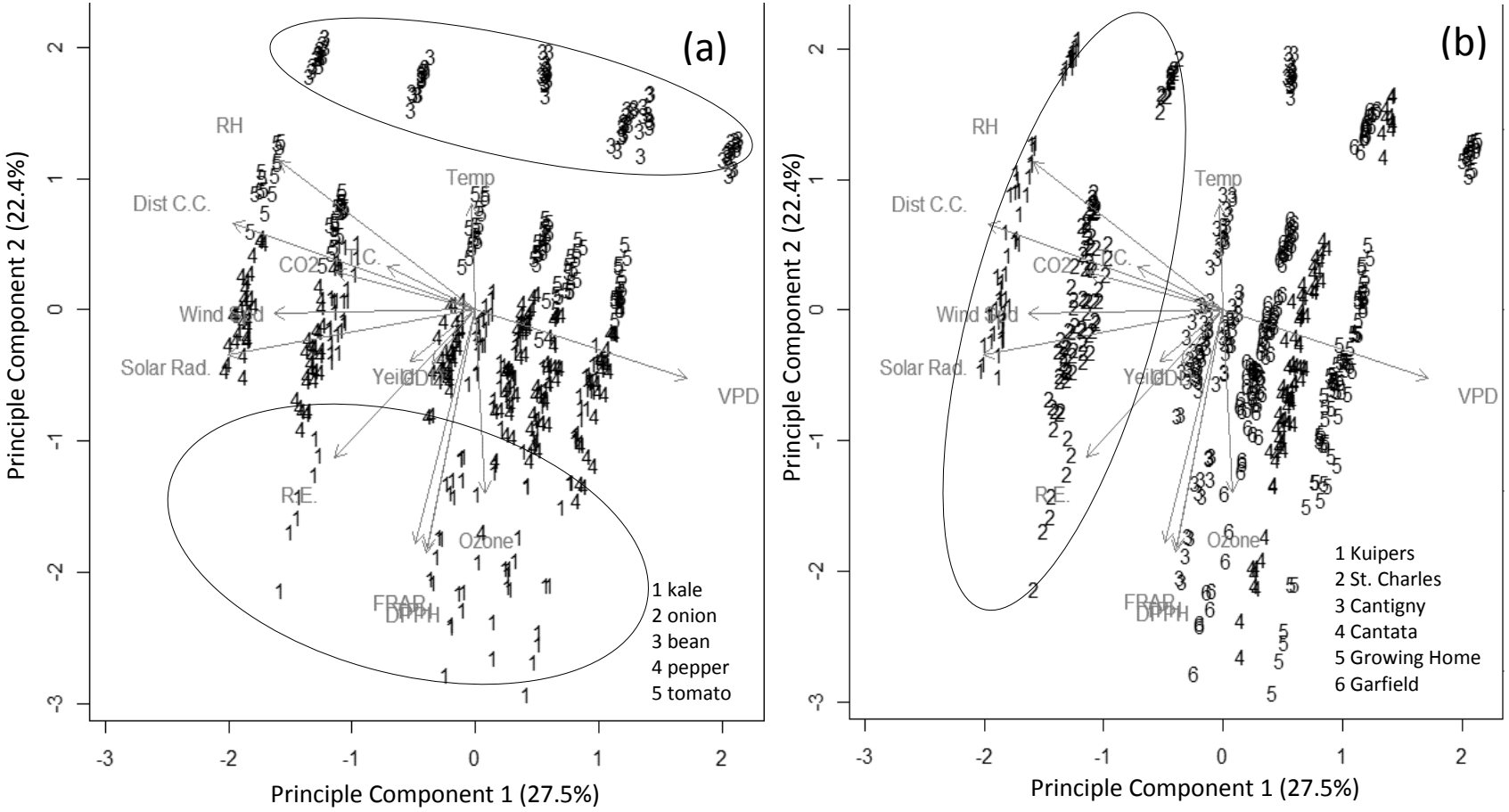

Fig. 3.4 First and second principle component of fruit quality measures FRAP, DPPH, and TPC compared to measures microenvironment factors in 2014. Panel (a) is the PCA analysis with the crop indicated by each point. Panel (b) points are indicating the garden location from most rural (Kuipers) to most urban (Garfield). For meaning of each environmental factor abbreviation, see Table 3.8.

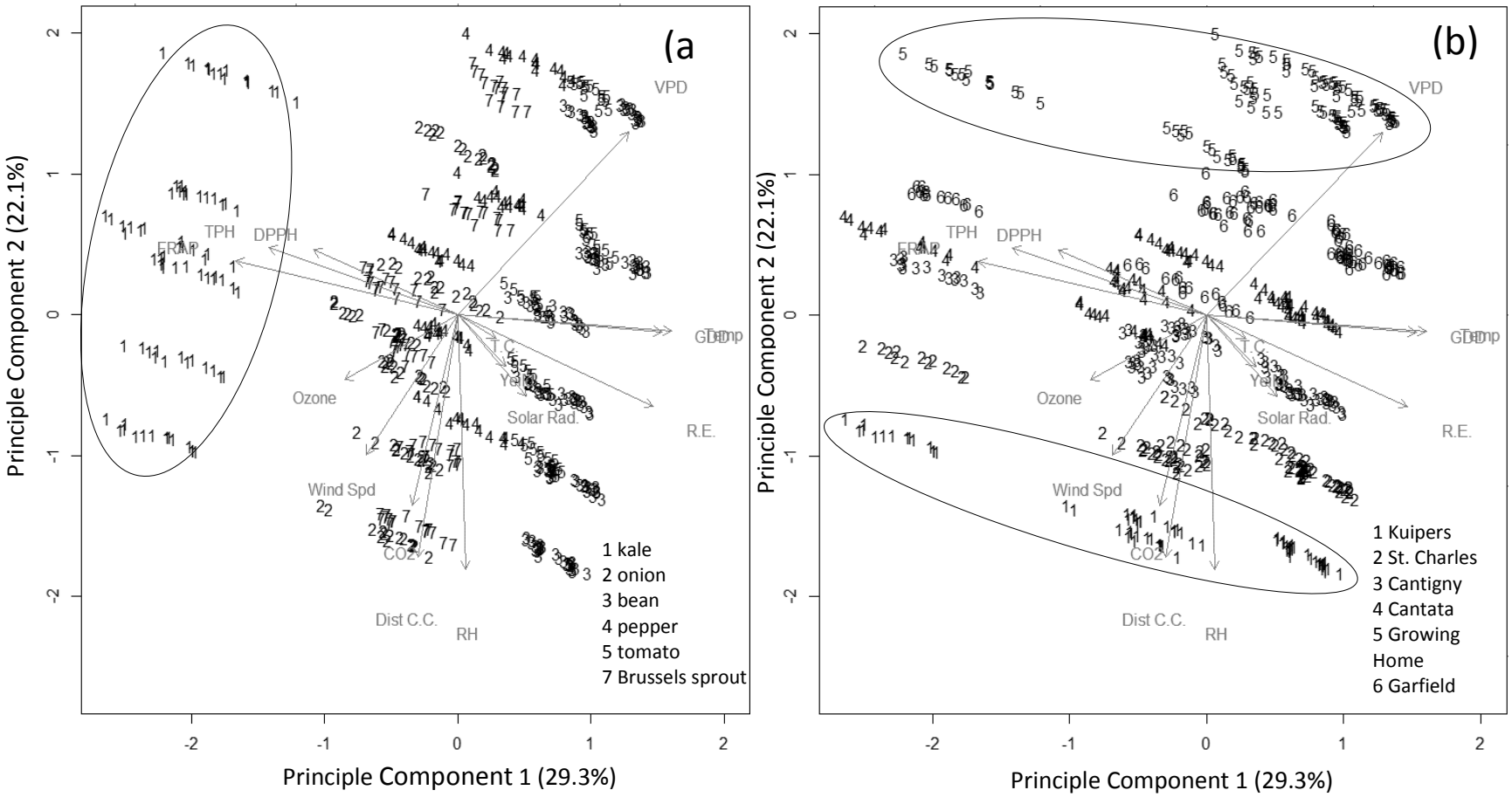

Fig. 3.5 First and second principle component of fruit quality measures FRAP, DPPH, and TPC compared to measures microenvironment factors in 2015. Panel a is the PCA analysis with the crop indicated by each point. Panel b points are indicating the garden location from most rural (Kuipers) to most urban (Garfield). For meaning of each environmental factor abbreviation, see Table 3.8.

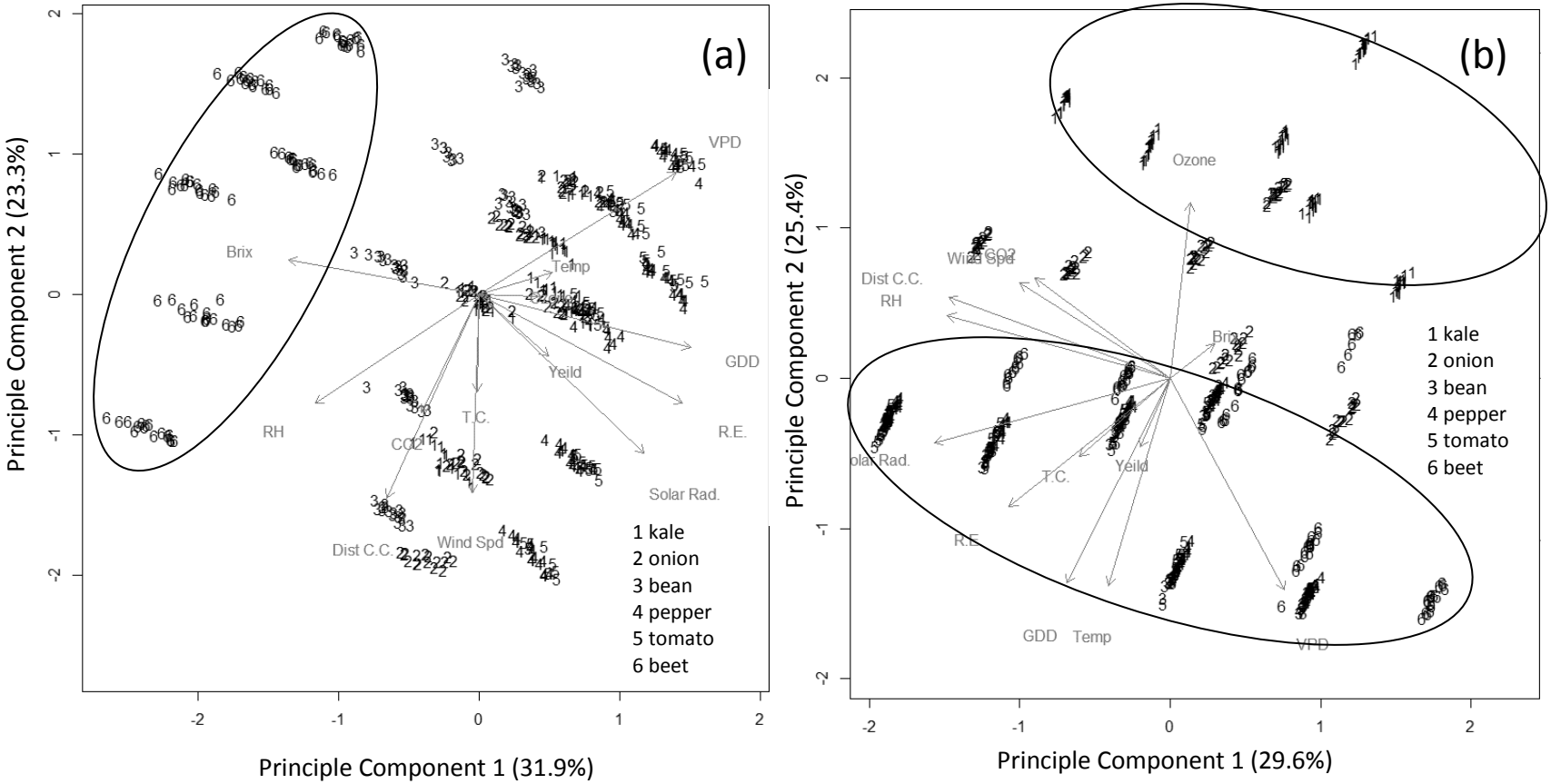

Fig. 3.6 First and second principle component of soluble solids compared to measures microenvironment factors. Panel a is the PCA analysis from 2014 with the crop indicated by each point. Panel b is from 2015. For meaning of each environmental factor abbreviation, see Table 3.8.

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CHAPTER 4: FARMING IN THE CITY: INSECT ABUNDANCE AND HERBIVORY AMONG URBAN, PERI-URBAN, AND RURAL VEGETABLE GARDENS

Abstract

As urban agriculture (UA) expands throughout the global north, research is needed to understand the ecology of urban agroecosystems. Insects, both beneficials and pests, have critical impact on the function and productivity of agroecosystems and it is likely that the urban environment will influence insect community dynamics. The objective of this study was to quantify insect pest abundance and herbivory in urban relative to rural agroecosystems. Insects were sampled weekly across two years with pheromone baited and yellow sticky traps at six raised bed garden sites across an urban to rural transect of Chicago, IL. Baited traps included *Helicopvera zea* (corn earworm), *Ostrinia nulilalis* (European corn borer), and *Trichoplusia ni* (cabbage looper) pheromones. Crops were scouted weekly for insect pest presence and herbivory. For insects collected via sticky traps, there was no difference in abundance or diversity among the six garden sites in either 2014 or 2015. Abundance of taxa Hymenoptera and Crisopidae were greater in 2014 across all sites, while Diptera, Coleoptera, *Diabrotica*, and Aphididae were greater in 2015. Thripidae, Hemiptera, Lepidoptera, and Aphidae did not differ between years. *H. zea* abundance was greater at the rural sites and was correlated ($r = 0.614$, $p < 0.001$) with distance from downtown Chicago. *T. ni* was not different among sites or years. Among the seven crops grown, only kale (*B. oleracea* spp. *viridis)*, tomato (*S. lycopersicum*), and Brussels sprout (*B. oleracea* spp. *gemmifera*) had significant herbivory damage. *Pieris rapae* (imported cabbageworm) herbivory in kale was greater at urban sites in 2015. *P. rapae* in Brussels sprout was greater in 2015, but unlike kale, damage was greater at rural sites. *Brevicoryne brassicae* (cabbage aphid), had greater coverage of Brussels sprouts at urban sites and *Macrosiphum euphorbiae* (potato

aphid) damage to tomatoes was greatest at an urban site in 2014. Aphid infestations were generally greater at urban sites, while Lepidoptera herbivory was generally greater at rural sites. Pest infestation was influenced in part by microclimatic factors and proximity to rural cropland.

Introduction

Urban agriculture (UA) can be defined as all forms of agricultural production that benefit from the infrastructure of human concentrations in towns or cities (Ellis and Sumberg, 1998; Vagneron, 2007). Urban agriculture in developed countries is on the rise (Mok et al., 2013; Opitz et al., 2016) and is already prevalent in much of the developing world (Hamilton et al., 2013). Urban agriculture can contribute to food security, urban waste utilization, economic revitalization, and ecological benefits (Smit and Nasr, 1992; McClintock, 2010; Gupta and Gangopadhyay, 2013; Goldstein et al., 2016). Despite the potential benefits of urban agriculture, there is limited research on the effects of urbanization on insect ecology within urban agroecosystems (Gregory et al., 2015).

Urbanization effects insect diversity (species richness) and abundance compared to natural systems (Frankie and Ehler, 1978), and urban effects on insects have been studied extensively (Pickett et al., 2008; McPhearson et al., 2016). Urban invertebrate species composition changes according to patch size (Bode and Maciejewski, 2014), land use type (McIntyre et al., 2001), diversity of vegetation (Lintott et al., 2014), and management (Shwartz et al., 2013). In highly fragmented industrial or residential areas, easily dispersed taxa are more abundant and sessile taxa tend to be less so (Denys and Schmidt, 1998), and species within taxa are less diverse (Knop, 2016). Predator species that require higher trophic diversity are less supported, which tends to favor greater herbivore abundance (Denys and Schmidt, 1998; McIntyre, 2000). Pollinators appear to be sufficiently abundant in urban environments (Matteson

et al., 2008), but increased garden and city park space does increase diversity and abundance (Matteson et al., 2013). Human social, economic, and cultural forces also determine ecological function that affect insect diversity and abundance, especially in respect to flora choices (Loram et al., 2008; Lovell and Taylor, 2013). Urban insect diversity loss is often driven by loss of habitat, insecticide spraying, and fragmentation (Jones and Leather, 2012).

The urban climate is altered and pollution levels are often elevated (Wortman and Lovell, 2013), and there is evidence that this affects insect abundance and diversity. Dale and Frank (2014) and Meineke et al. (2013) found that elevated urban temperatures (i.e., the urban heat island effect) drove significant increases in certain insect herbivores, including a 13-fold increase in abundance of the tree herbivore *Parthenolecanium quercifex*. Higher urban temperature increases the likelihood of overwinter insect survival, which can change ecological dynamics (Bale et al., 2002). Sulfur dioxide, and urban atmospheric pollutant, has been shown to change habits and evolutionary fitness of several Lepidoptera species (Bishop and Cook, 1980). Elevated ozone concentrations can contribute to plant stress which can lead to greater herbivory and herbivore abundance (Alstad et al., 1982).

Ecosystem services in respect to insect abundance and diversity is a recognized benefit of urban food and community (Philpott et al., 2013). In Phoenix, AZ, a desert environment, the highest diversity and abundance of ground dwelling arthropods were found in agriculture lands within the city limits (McIntyre et al., 2001). Home and community gardens have high flora diversity, which typically begets greater insect diversity (Jaganmohan et al., 2013; Lin et al., 2015). In Bangalore, India, domestic gardens contributed more to insect diversity than public parks or spaces (Jaganmohan et al., 2013). Matteson et al. (2013) found that small additions of native flowers did not increase diversity of natural predators or pollinators, but larger patches of

floral resources were likely needed to see changes. Abundance of the herbivore predator Coccinilidae (lady beetle) is often greater in gardens or farms that are more isolated in highly build areas because the gardens have the greatest food source in the area (Egerer et al., 2016).

Insect pests and herbivory can be a major limitation to successful urban food production (Gregory et al., 2015). Crops grown in urban gardens and farms of the U.S. are mostly non-native (Loram et al., 2008), and commonly include species in the Brassicaceae, Cucurbitaceae, Solanaceae and Fabaceae families (Gittleman et al., 2012; Taylor, 2016).Gregory et al. (2015) surveyed insect pests in 22 gardens in New York City and they observed the following: Aphids (*Aphis gossypii* and *Myzus persicae*; 18% of gardens) and spidermites (*Tetranychus urticae*; all gardens) were greatest in Solanaceae crops; squash bugs (*Anasa tristis*; 29% of gardens) and aphids (*M. persicae*; all gardens) were greatest in Cucurbitaceae crops; and whiteflies (*Aleyrodus proletella*; 91% of gardens), aphids (*A. gossypii* and *M. persicae*; all gardens), and flea beetles (*Phyllotreta spp.*; 33% of gardens) were prevelant in *Brassicaceae* crops. In a survey of the extensive agriculture land in Havana Cuba, Altieri et al. (1999) reported the most common pests were *Ascia monuste* (southern white butterfly), *Bemisia tabaci* (whitefly), *Frankliniella spp.* (thrips), *Empoasca spp.* (leaf hoppers), *Pseudococcus spp.* (mealy bugs), and *M. persicae* (aphids). Important annual vegetable pests in the U.S. include aphids (*M. persicae* and *B. brassicae*), Lepidoptera (*T. ni, Plutella xylostella, H. zea,* and *O. nibulalis*), whiteflies (*Trialeurodes vaporariorum, A. proletella,* and *Bemisia argentifolii*), and Coleoptera (*Diabrotica sp*. and Alticini (flea beetles)) (McKinlay, 1992). Not surprisingly, the pests that inhabit urban agroecosystems are similar to the pests that are found in rural agroecosystems and most have high dispersal ability (Moreira et al., 2016).

Understanding insect community dynamics within urban agroecosystems will contribute to improved pest management strategies and greater productivity and profitability of urban gardens and farms. The objective of this study was to quantify insect herbivory and abundance of insect taxa relevant to annual vegetable production systems across and urban to rural transect of Chicago, IL.

Materials and Methods

Garden Design

Six sites were chosen in the Chicago, IL area along a latitudinal corridor close to 41° 50' N, ranging from near the city center to rural agricultural areas (Fig. 4.1). Each site included a garden with forty 0.43 m^3 containers (Smartpot™, High Caliper Growing Systems, Oklahoma City, OK) filled with a compost-soil mix. Yearly soil tests indicated adequate soil nutrients for optimal crop growth. Two cultivars of seven common vegetable crops were planted across three intervals including spring planting of kale (*B. oleracea* cvs. *Toscano* and *Winterbor*) and onion (*Allium cepa* L. cvs. Candy and Red Zeppelin), summer planting of tomato (*Solanum lycopersicum* L. cvs. *Bush Goliath* and *Virginia Sweet*), sweet pepper (*Capsicum annuum* L. cvs. *Bounty* and *Antohi Romanian*), and snap bean (*Phaseolus vulgaris* L. cvs. *R123* and *S156*), and fall planting of table beet (*Beta vulgaris* spp. *vulgaris* cvs. *Merlin* and *Chioggia*) and Brussels sprout (*B. oleracea* spp. *gemmifera* cvs. *Diablo* and *Long Island*). Cultivars included an heirloom and hybrid type (the first mentioned cultivars above are the hybrids). Eight replications of each cultivar were included in each garden. Soil moisture was maintained at or near field capacity with drip irrigation, and soil moisture was monitored with moisture sensors (200SS Watermark Sensors, Irrometer Inc, Riverside, CA).

Microclimate Measures

Weather towers were located directly adjacent to each experimental garden and equipped with microclimate and trace gas sensors and data loggers (CR10X, Campbell Scientific, Logan, UT). Sensors included a HMP45 temperature and relative humidity probe (Campbell Scientific, Logan, UT), cup anemometer and wind vein (Davis Instruments Corp, Hayward, CA), SP-110 pyranometer (Apogee Instruments Inc., Logan, UT), SBA-5 CO_2 infrared gas analyzer (IRGA) (PP Systems Inc., Amesbury, MA), and an F-12 toxic gas analyzer with 0-1000 parts per billion (ppb) ozone sensor (Analytical Technology, Inc., Collegeville, PA). Microclimate data were averaged or summed for the period of time from planting to when insect and herbivory data was collected.

Site Descriptions

For the purposes of discussion, test sites were classified as urban (Garfield Park and Growing Home), peri-urban (Cantata and Cantigny), and rural (St. Charles and Kuipers) based on their proximity to the Chicago city center (Fig 4.1). The Kuipers garden was located within a 150 hectare agro-tourism farm and the field on three sides of the garden was pumpkins in 2014 and winter rye chopped for forage in 2015. The other side was a parking lot for farm machinery. Surrounding the farm was an abundance of corn and soybean cropland, typical of northern Illinois rural landscapes. The St. Charles garden was surrounded by turf at a horticultural research farm. The garden was approximately 40 meters from a busy highway; other neighboring land uses include residential housing, corn cropland, and turf grass playing fields. The Cantigny garden was adjacent to a narrow strip of urban forest, separating the garden from a busy highway. In addition, turf grass, a 250 hectare public park with ornamental gardens, and mixed suburban land uses (e.g., residential and commercial) surrounded the garden. The Cantata garden

was situated within a clearing of urban trees and surrounded by turf grass. Several busy roads and a large municipal zoo were located within 1 km of the garden. One urban garden, Growing Home, was located on the outer perimeter of an existing 0.5 ha urban farm. Several busy and residential roads surrounded the farm along with a high density of residential and vacant lots. The other urban garden, Garfield, was directly adjacent to a large glasshouse plant conservatory and outdoor ornamental and tree nursery. Similar to Growing Home, Garfield was nested within a neighborhood characterized by high density residential housing and many vacant lots. Environmental conditions were variable across the urban to rural gradient (Table 4.1).

The microclimate of the sites is described as follows (Table 4.1). Overall, temperatures were 0.9 and 1.7 °C warmer at urban gardens compared to rural during the daytime and nighttime, respectively (i.e., urban heat island effects). Season long base 10°C growing degree day accumulation was 12% greater at urban compared to rural gardens. There was an average increase of 22 frost free days in the urban gardens compared to the rural gardens. Total radiant exposure was greatest at rural gardens, which was 8.5% greater than at urban gardens and 11% greater than at peri-urban gardens. Transmission coefficient of the canopy, a measure of the canopy cover, was similar (about 0.93) in urban and rural gardens, but 34% lower in peri-urban gardens (0.65).

Insect Traps

Scentry Multiguard (Scentry Biologicals, Inc., Billings, MT) two sided flight intercept yellow sticky traps with 232 cm^2 tangle-foot area were attached to stakes horizontally at 1.1 meters above the surface of the raised beds in the center of each garden. Traps were covered with shrink wrap and placed in a freezer for identification and replaced every week. Pherocon VI plastic covered traps (Trécé Inc., Adair, OK) – with a 186 cm^2 sticky trap and a rubber

pheromone baited lure for *Trichoplusia ni* (TR-CL 3119, Trécé Inc.) in the center of the sticky trap – were attached to the stake of the sticky traps (1.1. m above raised-bed surface). Counts of *T. ni* were recorded weekly and insects were removed from trap. Two one meter conical vinyl mesh nets with a trap chamber (*Heliothis* trap, Scentry) with opening at 50 cm from top of raised beds were located on the outer perimeter of each garden. Rubber pheromone lures for *Helicoverpa zea* (HC-CEW 100337, Scentry) and *Ostrinia nibulalis* (TR-ECB I 3110, Trécé) were pinned to the opening of the conical traps. Traps were emptied weekly into plastic bags and stored in a freezer. Pheromone lures were replaced every three weeks throughout the growing season. Traps were deployed in the first week of June in 2014 and the third week of May in 2015. Insects from traps were collected until the first week of October in both years.

Identification of insects on sticky traps was done by order and several families, genus, and species that were either important pest or predator taxa according to Marshall (2006). Orders Diptera and Hymenoptera, and much of Hemiptera were not readily distinguishable into families, but diversity within each taxa appeared to be limited.

Vegetable Insect Infestations

Insect prevalence and herbivory was visually assessed and rated each week. *Pieris rapae* in kale and Brussels sprout was quantified by estimating the percentage of leaf damage on individual leaves across plants with each experimental unit. *Brevicoryne brassicae* infestation in Brussels sprout was quantified from visual estimates of percent leaf coverage by the aphid. *Macrosiphum euphorbiae* on tomato caused distinctive leaf rolling in the shoot meristematic tissue of the plant. Damage from *M. euphorbiae* was estimated by percentage visual ratings of leaf rolling. Because crop yield was an important variable in the broader experiment, insect infestations were managed when necessary using products approved for use in USDA certified

organic systems (OMRI-approved). After leaf rolling data was collected in tomato, aphids were sprayed with neem oil (Triple action neem oil, Southern Ag, Hendersonville, NC) weekly. Management of *P. rapae* was not necessary in kale, but Brussels sprout was sprayed with *Bacillus thuringiensis* subspecies *kurstaki* concentrate (Thuricide BT Caterpillar Control, Southern Ag, Hendersonville, NC) weekly during the first six weeks after transplanting in 2015. *B. brassicae* in Brussels sprout was not managed due to the late date of infestation. Of the seven crops included in the experiment, tomato, kale, and Brussels sprout were the only species with notable herbivory damage.

Statistical Analysis

Weekly sticky trap and pheromone bait trap captures were summed across all weekly samples for each site and site comparison was made with year as replicate. Analysis of variance comparisons using linear mixed models were made using the *nlme* package (Pinheiro et al, 2015) in R (R Core Team, 2016). Site location was considered a fixed effect, while year and year by site were considered random effects. The values of captures were natural log or square root transformed prior to analysis, when necessary, to homogenize variances and normalize residuals. Post hoc separation of least squares means was done using Tukey's honest significant difference (HSD) adjustment with a significance level of α=0.05 using the HSD function in the agricolae package (Mendiburu, 2016) of R. Pearson's correlation analysis as used to explore possible relationships between microclimatic data and insect abundance using the *rcorr* function in R.

Herbivory was analyzed from the eight replicate plots of each variety at each site. Herbivory among sites was compared with linear mixed model analysis of variance using *nlme* package in R. Fixed effects in the model were site, variety, and site by variety interactions of crop while random effects were year, blocking factor, and interactions of year to other factors.

Transformations of data were performed on data as described in the previous paragraph. Post hoc separation of least squared means was done using Tukey's honest significant difference (HSD) adjustment with a significance level of α=0.05 using the HSD function in the agricolae package (Mendiburu, 2016) of R. Least squares means were back transformed for comparison in figures, but standard errors are excluded from transformed data because standard errors could not be back-transformed.

Results

Sticky Trap Captures

Thrips and flies made up the majority of sticky trap captures in both years of the study (Table 4.2).Of the total captures, Thripidae species accounted for 82% in 2014 and 69% in 2015, while Diptera species represented 14% and 27% in 2014 and 2015, respectively. All other insect taxa represented less than 2% of total captures in either year. Total sticky trap captures (P = 0.653), Thripidae species (P = 0.788), Hemiptera species (P = 0.798), Lepidoptera species (P = 0.997), Coccinilidae species (P = 0.855), and Aphidae species (P = 0.887) did not differ between years. Hymenoptera species ($P < 0.001$) and Crisopidae species (P = 0.0097) captures were greater in 2014 ($P < 0.001$) while Diptera species (P = 0.0238), Coleoptera species (P = 0.0206), and Aphididae species (P = 0.0476) were greater in 2015 (Table 4.2). Site location ($P > 0.28$) or site by year ($P > 0.11$) was not significant for any of the taxa sticky trap captures. The tangle-foot substance made identification within the Diptera, Hemiptera, and Hyminoptera orders difficult and diversity indices could not be calculated. Weekly captures (Fig. 4.2) show that Thripidae captures (panel a) peaked early while Chrysopidae and Aphididae species (Fig 4.2 panels e and f, respectively) peaked later in the season. Diptera, Hemiptera, and Coleoptera

species captures had different peaks depending on the year (Fig. 4.2 panels b, c, and d respectively).

Hormone Bait Traps

Helicopvera zea (corn earworm) abundance had significant year by site interaction ($P < 0.001$, Table 4.3) The majority of captures of *H. zea* were obtained in weeks 13, 14, and 15 (late August through early September, Fig. 4.3). Square root transformed captures of *H. zea* from these three weeks was correlated to the distance to city center ($r = 0.626$, $P < 0.001$, Table 4.4). *Ostrinia nibulalis* (European corn borer) captures did not differ between years ($P = 0.0808$) or among sites ($P = 0.256$) or the interaction between year and site ($P = 0.815$, Table 4.3). Captures of *Trichoplusia ni* (cabbage looper) were not different between years (P = 0.057) or site ($P = 0.256$).

Vegetable Crop Insect Herbivory

Kale had leaf herbivory damage from *P. rapae* (imported cabbage worm) which was the only species observed feeding. Percent leaf herbivory damage of kale had site by variety difference ($P = 0.0126$, Fig. 4.4). The most urban site, Garfield, had less damage from *P. rapae* than other sites in both cultivars (Fig. 4.4). *M. euphorbiae* (potato aphid) herbivory on tomato, as quantified by percent leaf rolling, was different among sites ($P = 0.011$), but was not different between cultivars ($P = 0.861$) or years ($P = 0.216$). The urban site, Growing Home, had greater leaf rolling than the other sites (Fig. 4.5).

Brussel sprout had leaf herbivory damage from *P. rapae* and late season (October) herbivory damage from *B. brassicae* (cabbage aphid). There was no difference between cultivars in *B. brassicae* leaf coverage in Brussels sprout. Leaf coverage of *B. brassicae* was different among sites ($P < 0.001$) at the urban sites, Garfield and Growing Home, and were greater than all

other sites (Fig. 4.5). The two rural sites, Kuipers and St. Charles, had greater leaf damage from *P. rapae* than the urban site, Garfield (Fig. 4.6).

Discussion

Taxa abundance sampled with sticky traps was not different among gardens in this study. Sticky traps are used to catch insects with relatively good dispersal ability (Chen et al., 2004), which is likely why the majority of captures were Diptera and Thripidae species that have demonstrated long range dispersal behavior (Thripidae - Smith et al., 2015, Diptera - Adler et al., 2005). In general, most species with high dispersal ability will maintain abundance if the environment is conducive to supporting them, although the polyphagous predators and parasitoid insects tend to decrease as patches become more isolated because they require complex habitats (Denys and Schmidt, 1998). Bode and Maciejewski (2014) found that species with dispersal ability were found often in 97 patches of goldenrod (*Solidago* spp.) in Buffalo, NY, but sessile species were less likely to be present especially in small patch sizes. Gardiner et al. (2014) found that most generalist predator species had similar abundance between urban gardens and abandoned land, which was demonstrated in this study by both Chrysopidae and Coccinilidae species abundance not changing among sites. Gardiner et al. (2014) also found that higher trophic level species became more abundant over time, which may explain the difference between years on some of the taxa as the gardens were established in 2013 and insect communities may change as the site increases endemic species.

Some notable species that were not observed in the sticky traps included Syriphidae species, *Popillia japonica*, and *P. rapae*; however, these were sighted several times in the gardens. These species are important vegetable pests and *P.* rapae caused herbivory in both *Brassica* crops. The pheromone bait trap captures from the cone traps, other than the target

species, were identified and the Syriphidae species, *Popillia japonica*, and *P. rapae* were captures in both years with highest counts of *P. japonica* in the peri-urban site, Cantigny, and *P. rapae* in the urban site, Growing Home (data not shown). It was observed that *P. japonica* were more abundant at Cantigny in and around the garden.

The larvae of *H. zea* (corn earworm) is a polyphagous crop herbivore and a pest on many important field and vegetable crops, and migrates from the southern U.S. because they cannot overwinter above latitude 40°N (Fitt, 1989; Boyd et al., 2008). The most abundant food source for *H. zea* larvae in the Midwest is maize (*Zea mays*) and the adults move until they find a food source (Sandstrom, 2007; Westbrook and López, 2010). The migratory nature of adult *H. zea* can be observed in the weekly capture data around week 14 (Figure 4.3), and greater abundance in rural gardens can likely be explained by proximity to its major landscape food source – maize (Table 4.2). *O. nubilalis* larvae is also primarily a pest of maize, but populations of adults were so low across all sites that no trends could be elicited. *T. ni* is mainly a vegetable crop pest and also does not overwinter in northern Illinois, although there was no difference among sites and no clear adult migratory pattern in the data.

Of the seven crops grown, the two *Brassica* crops had three herbivore infestations and only tomatoes out of the other five crops had any significant herbivory damage. Brassicaceae crops are widely grown and have many natural pest species. Gregory et al. (2015) and Altieri et al. (1999) found insect infestations on Brassicacea, Curcubitacae, and Solanaceae were the most abundant and problematic to urban farmers and gardeners, likely because these are the most abundant crops grown. The urban site, Growing Home, had greater pest infestation in kale, tomato, and Brussel sprout compared to the other sites and was adjacent to a 0.5 hectare organic urban farm, which could explain the increased pest prevalence. The proximity to host plants and

higher pest population is similar to the findings with *H. zea* in the rural sites. The urban site, Garfield, had low *P. rapae* infestations (Figs. 4.4 and 4.6) and was the most urbanized of all the sites. There was no evidence to suggest a correlation between insect captures and herbivory of the crops.

Aphididae species infestations were greater in the urban environment (Figs. 4.4 and 4.5). In Brussels sprouts, the *B. brassicae* was not present until late September and was not present outside of urban sites. The first frost date of the urban sites were 11 and 22 days later that the other sites in 2014 and 2015 respectively (Table 4.1) and likely affected the abundance outside the urban sites. Dale and Frank (2014) found that the urban heat island was the most important factor in *M. tenebricosa* infestation of maple trees in Raleigh NC. Denys and Schmidt (1998) found increased pest prevalence, including aphids, in *Artemisia vulgaris* at urban compared to rural sites and related the effect to reduced predator and parasitoid abundance at urban sites. No other studies linking aphid infestation to urbanization were found and further research could explore possible links in urban agriculture.

Conclusion

This study found that the insect community in urban gardens did not widely vary between the rural and urban environment, but the species *H. zea* had greater abundance at rural sites likely due in part to the proximity of maize – a common host species. Herbivory was present on three crop species out of seven crops grown, including two Brassicaceae species. Infestations included two Aphididae species and *P. rapae.* Aphid infestation was greater in the urban sites, and was likely influenced by increased frost free days and proximity to an adjacent urban farm. In addition to the urban heat island effect, proximity to urban farms, urban forests, and field crops may contribute to insect community dynamics across metropolitan regions. As urban population

increases and interest in urban agriculture grows, understanding the insect community dynamics within urban agriculture will contribute to best management practices for urban farmers.

Tables

	Location	Temperature	Last Frost	First Frost	Frost Free Days	Relative Humidity	Wind	CO_2	Ozone	AOT40	VPD	GDD (10°C)	Leaf Area Index	Transmission Coefficient	Radiant Exposure	Sun Hours	Distance to City
		°C				*%*	*m s^{-1}*	*ppm*	*ppb*		*kPa*				*J m^{-2}*		*km*
2014	**Kuipers**	15.3	16-Apr	30-Oct	197	75.1	2.14	361	23.1	60306	0.529	1552	0.07	0.96	3798	1620	77.5
2014	**St. Charles**	15.5	16-Apr	19-Oct	186	73.7	1.56	382			0.574	1596	0.19	0.91	3809	1613	60.9
2014	**Cantigny**	15.8	16-Apr	19-Oct	186	73.4	0.89	389	29.5	51173	0.592	1635	0.38	0.72	3565	1464	43.5
2014	**Cantata**	16.0	16-Apr	19-Oct	186	70.4	0.93	397			0.651	1647	0.77	0.57	3442	1315	18.2
2014	**Growing Home**	16.5	16-Apr	1-Nov	199	64.5	1.04	397			0.771	1715	0.25	0.88	3604	1508	11.2
2014	**Garfield**	16.9	15-Apr	2-Nov	201	67.0	1.41	398	17.1	37015	0.747	1788	0.03	0.98	3575	1466	7.5
2015	**Kuipers**	16.3	24-Apr	17-Oct	176	75.0	2.04	390	11.2	2100	0.549	1694	0.07	0.96	3828	1414	77.5
2015	**St. Charles**	16.3	24-Apr	17-Oct	176	74.6	1.30	379	13.1	6349	0.568	1717	0.19	0.91	3664	1357	60.9
2015	**Cantigny**	16.5	24-Apr	17-Oct	176	73.9	0.82	398	18.5	9722	0.592	1730	0.38	0.72	3362	1243	43.5
2015	**Cantata**	16.8	24-Apr	18-Oct	177	71.3	0.75	407	34.2	39771	0.660	1782	0.77	0.57	3243	1185	18.2
2015	**Growing Home**	16.7	23-Apr	8-Nov	199	61.7	0.97	401	2.1	268	0.843	1724	0.25	0.88	3455	1296	11.2
2015	**Garfield**	17.5	4-Apr	14-Nov	224	65.1	1.36	399	7.8	2451	0.809	1888	0.03	0.98	3459	1293	7.5

Table 4.1 Season average and accumulated measures calculated from environmental data collected at each of six gardens across the Chicago, IL metro region. Frost free days is the total days between the last and first frost (Temperature ≤ 0°C). AOT40 is sum of part per billion hourly ozone average minus 40 if ozone average is over 40 ppb (Σ(ppb h – 40)). VPD is vapor pressure deficit. GDD is growing degree days with base temperature of 10°C. Leaf Area index and transmission coefficient is calculated from fish eye photo analysis. Radiant exposure is the integration of the light irradiance measures. Sun hours is a measure of total daytime (0500 to 1900) hours where solar radiation is above 65% of maximum radiation. The Distance to city is a measure from the same point in downtown Chicago.

		Total Count	Thripidae	Diptera	Coleoptera	Hemiptera	Hymenoptera	Lepidoptera	Chrysopidae	Aphididae	Coccinilidae	Cicadellidae	Apidae	Diabrotica
			Thrips	Flies	Beetles	Half-wings	Wasps	Moths	Lacewings	Aphids	Lady Beetles	Leaf Hoppers	Bees	Cucumber Beetles
2014	Kuipers	9109	7547	1304	98	77	116	0	8	30	6	1	0	0
	St. Charles	3563	2458	863	94	89	78	2	4	57	3	15	1	0
	Cantigny	11344	10729	345	140	73	93	1	8	34	7	28	0	0
	Cantata	8557	7681	601	117	126	74	3	2	42	5	65	0	0
	Growing Home	7127	5247	1459	71	69	192	2	1	15	2	41	0	0
	Garfield	5930	4191	1546	63	198	61	0	5	42	11	7	4	0
2015	Kuipers	9092	5448	3284	199	104	54	3	1	55	8	7	2	0
	St. Charles	6013	3193	2522	160	97	40	1	1	95	4	10	0	2
	Cantigny	11300	8989	1848	334	183	26	0	0	115	4	66	0	0
	Cantata	8116	6553	1283	186	56	35	3	0	20	3	53	0	0
	Growing Home	11136	7512	3150	270	168	35	1	0	67	7	38	0	2
	Garfield	6271	3992	2083	113	64	18	1	2	36	4	4	3	3

Table 4.2 Total insect captures from yellow sticky traps with a tangle-foot compound from May to October of 2014 and 2015 across an rural to urban gradient in Chicago, IL. Insects were collected and sticky traps were replaced weekly throughout the season.

		Helicopvera zea	*Ostrinia nubilalis*	*Trichoplusia ni*
2014	**Kuipers**	171	2	12
	St. Charles	18	3	9
	Cantigny	5	0	2
	Cantata	0	0	8
	Growing Home	2	0	5
	Garfield	4	5	26
2015	**Kuipers**	49	3	28
	St. Charles	28	6	8
	Cantigny	6	1	4
	Cantata	10	12	9
	Growing Home	10	8	15
	Garfield	4	2	11

Table 4.3 Total insect captures from pheromone bait traps from May to October of 2014 and 2015 across site sites in Chicago, IL. Insects were collected from traps weekly throughout the season.

	Site	Count	Distance
2014	Kuipers	146	77.5
	St. Charles	15	60.9
	Cantigny	5	43.5
	Cantata	0	18.2
	Growing Home	2	11.2
	Garfield	0	7.5
2015	Kuipers	49	77.5
	St. Charles	19	60.9
	Cantigny	1	43.5
	Cantata	0	18.2
	Growing Home	0	11.2
	Garfield	1	7.5

Table 4.4 Captures of *Helicopvera zea* from weeks 13, 14, and 15 and distance to city center in km from each site. Within year least squared means separation was from Tukey HSD (α = 0.05).

Figures

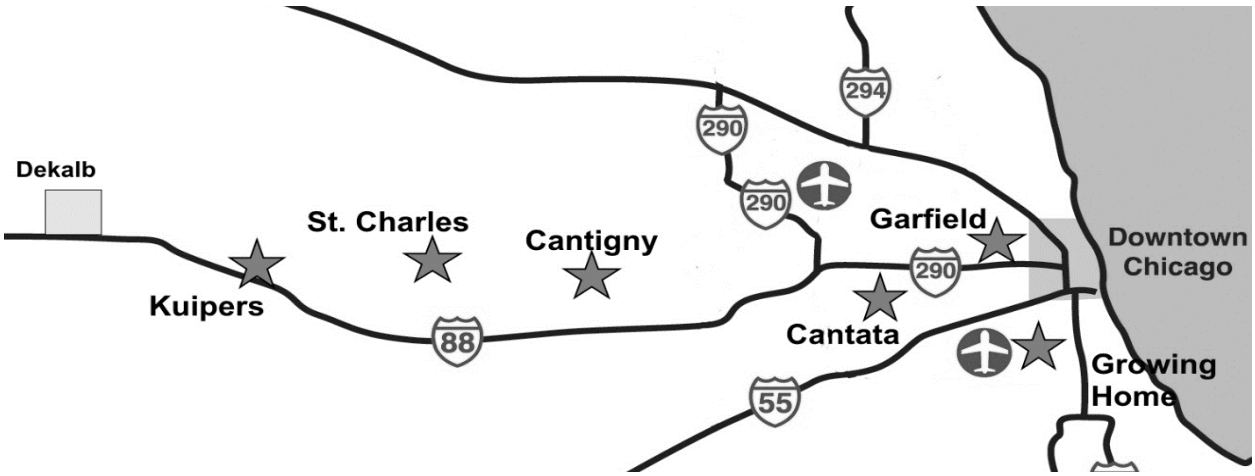

Fig. 4.1 Map of experimental garden sites across the Chicago, IL metro region. Sites are indicated by stars and adjacent labels. 'Rural' gardens included Kuipers and St. Charles, 'peri-urban' gardens include Cantigny and Cantata, and 'urban' gardens included Garfield and Growing Home.

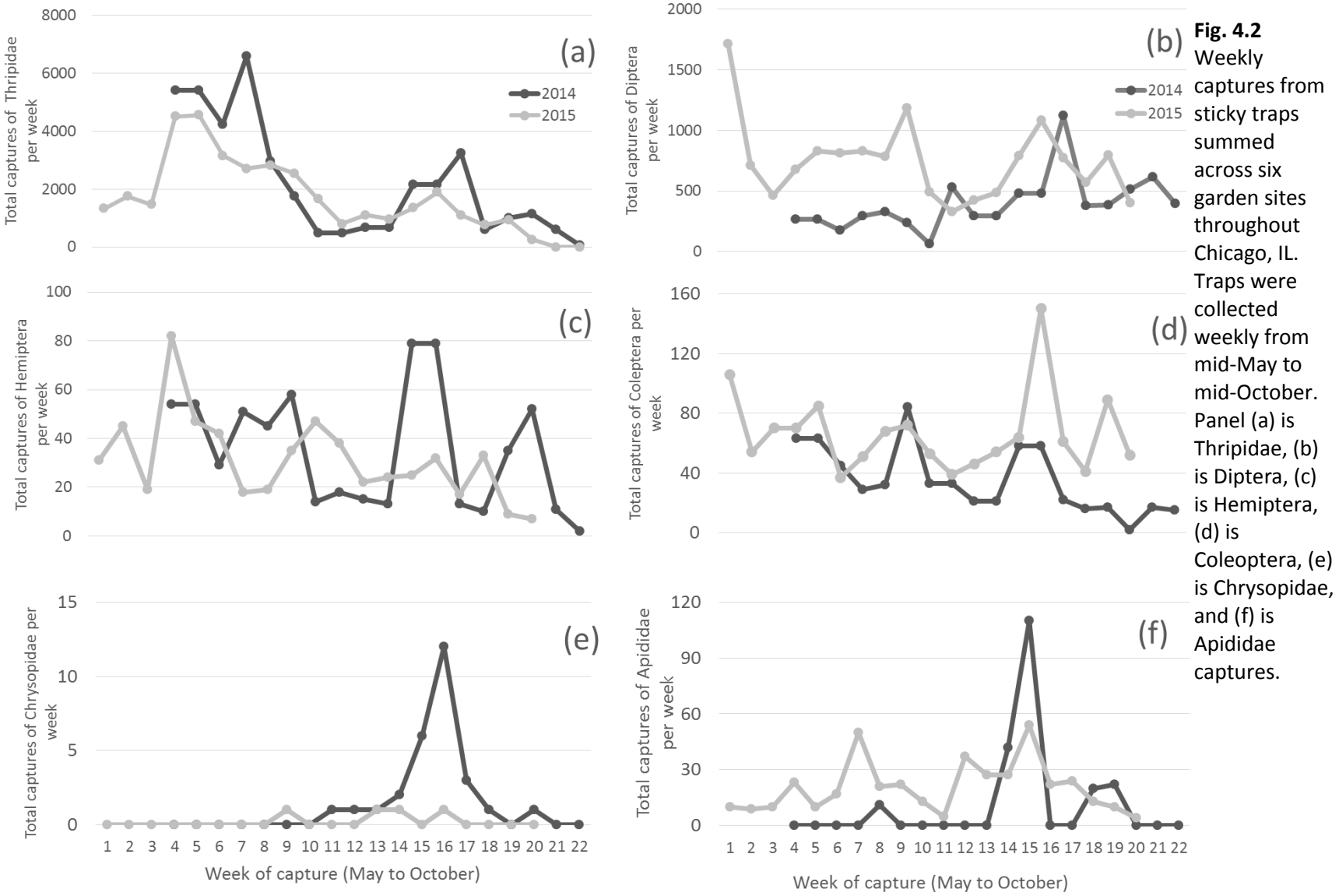

Fig. 4.2 Weekly captures from sticky traps summed across six garden sites throughout Chicago, IL. Traps were collected weekly from mid-May to mid-October. Panel (a) is Thripidae, (b) is Diptera, (c) is Hemiptera, (d) is Coleoptera, (e) is Chrysopidae, and (f) is Apididae captures.

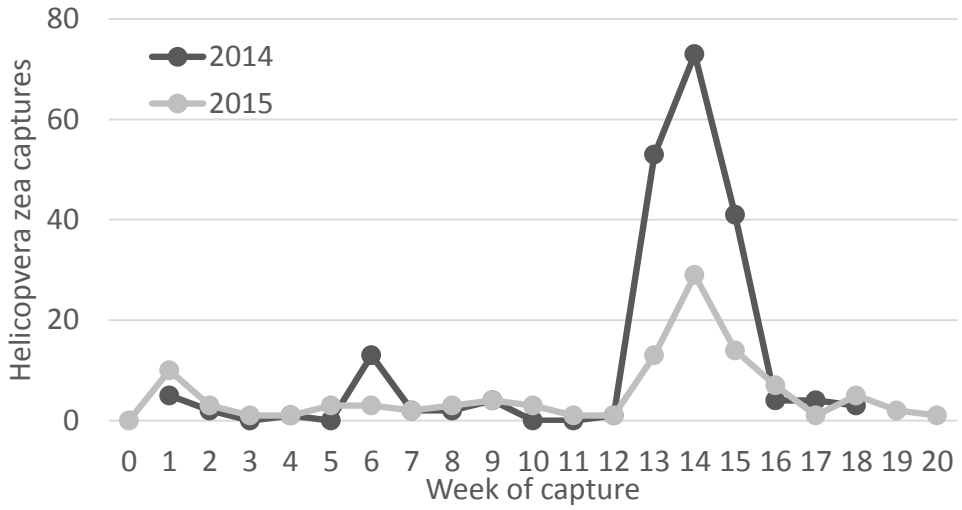

Fig. 4.3 Total weekly captures of *Helicopvera zea* from mid-May to mid-October of 2014 and 2015 from six sites in rural to urban transect of Chicago, IL.

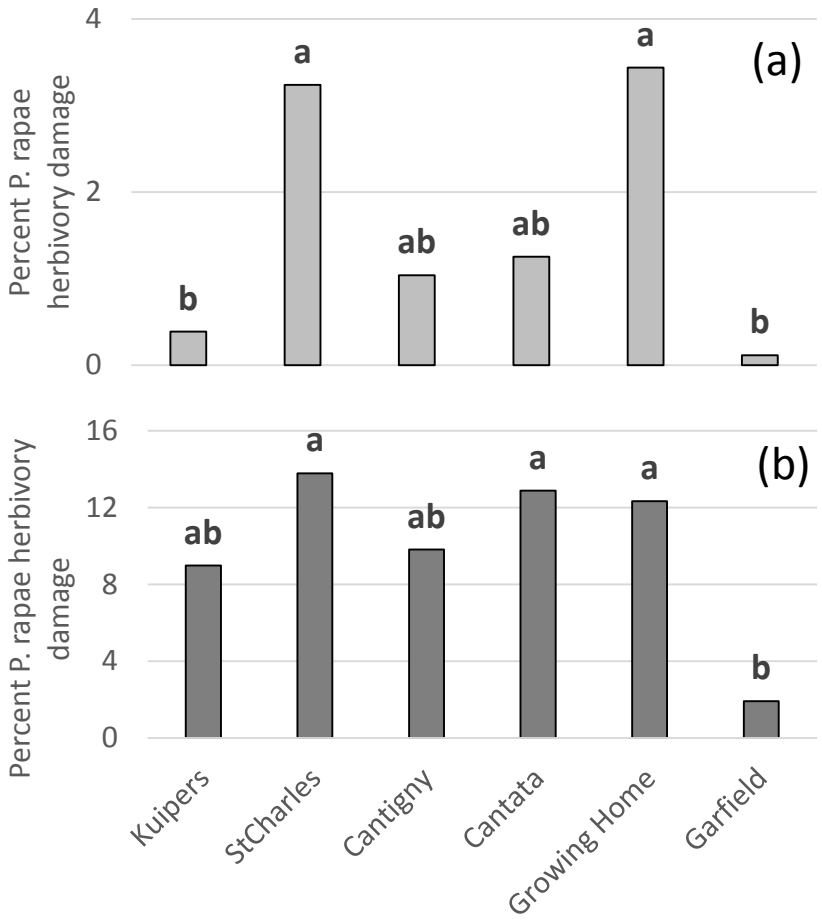

Fig. 4.4 Percent herbivory damage from *Pieris rapae* on kale leaves across six sites in Chicago, IL. Values are pooled across years for analysis. Letters indicate differences between sites based on Tukey's honest significant difference (α = 0.05). Least squares means were back-transformed after square-root transformation and standard error values could not be back-transformed. Panel (a) is hybrid variety 'Winterbor' and (b) is heirloom variety 'Toscano'.

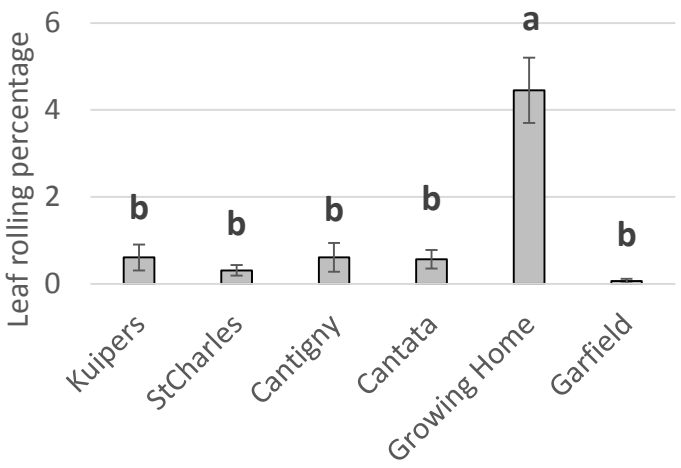

Fig. 4.5 Percent leaf rolling of tomato plants caused by *Macrosiphum euphorbiae* across six sites in Chicago, IL. Values are pooled across years for analysis. Letters indicate differences between location based on Tukey's honest significant difference (α = 0.05) and ns signifies no significant difference. Error bars are standard errors of least squares means.

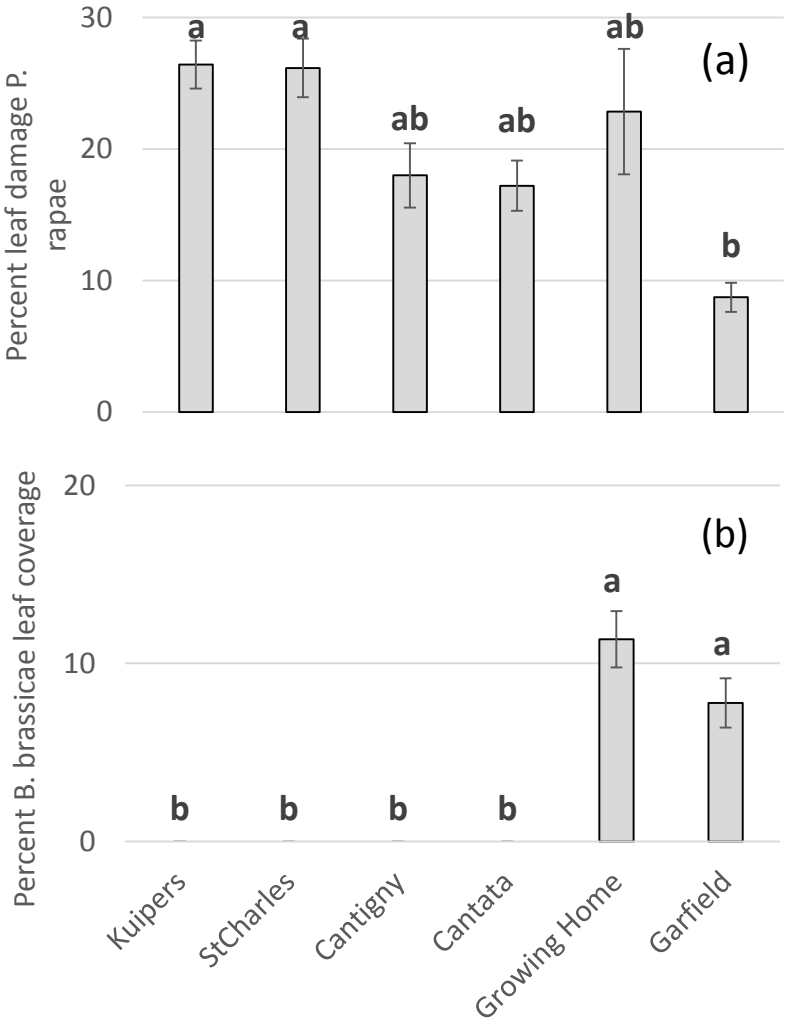

Fig. 4.6 Least squares means of percent leaf damage by *Pieris rapae* (b) and leaf coverage by *Brevicoryne brassicae* (a) in Brussel sprout across six sites in Chicago, IL. Values are pooled across years for analysis. Letters indicate differences between sites based on Tukey's honest significant difference (α = 0.05). Error bars are standard errors of least squares means.

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